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Influence of Variables on the Consolidation and Unconfined Compressive Strength of Crushed Salt

Technical Report

January 1987

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Tom W. Pfeifle
Paul E. Senseny
Kirby D. Mellegard
of
RE/SPEC Inc.

prepared for

Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201-2693

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Office of Nuclear Waste Isolation

BATTELLE Project Management Division

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ABSTRACT

Eight hydrostatic compression creep tests were performed on crushed salt specimens fabricated from Avery Island dome salt. Following the creep test, each specimen was tested in unconfined compression. The experiments were performed to assess the influence of the following four variables on the consolidation and unconfined strength of crushed salt: grain size distribution, temperature, time, and moisture content. The experiment design comprised a half-fraction factorial matrix at two levels. The levels of each variable investigated were grain size distribution, uniform-graded and well-graded (coefficient of uniformity of 1 and 8); temperature 25°C and 100°C; time, 3.5 x 10^3s and 950 x 10^3s (approximately 60 minutes and 11 days, respectively); and moisture content, dry and wet (85 percent relative humidity for 24 hours). The hydrostatic creep stress was 10 MPa. The unconfined compression tests were performed at an axial strain rate of 1 x $10^{-5}s^{-1}$. Results show that the variables time and moisture content have the greatest influence on creep consolidation, while grain size distribution and, to a somewhat lesser degree, temperature have the greatest influence on total consolidation. Time and moisture content and the confounded two-factor interactions between either grain size distribution and time or temperature and moisture content have the greatest influence on unconfined strength.

FOREWORD

The National Waste Terminal Storage program was established in 1976 by the U.S. Department of Energy's predecessor, the Energy Research and Development Administration. In September 1983, this program became the Civilian Radioactive Waste Management (CRWM) Program. Its purpose is to develop technology and provide facilities for safe, environmentally acceptable, permanent disposal of high-level waste (HLW). HLW includes wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes from production of nuclear weapons, and solidified wastes from fuel reprocessing.

The information in this report pertains to the rock mechanics studies of the Salt Repository Project of the Office of Geologic Repositories in the CRWM Program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 BACKGROUND

Backfilling the emplacement rooms and access drifts of a deep geologic nuclear waste repository in rock salt with native mine-run ore (crushed salt) is an attractive option under consideration by repository designers. The perceived benefits of the backfilling are (1) haulage and spoiling of the mine-run ore will be reduced significantly; (2) repository permeability, at least locally, will be reduced if the backfill is consolidated significantly by creep deformations of the roof, floor, and rib of the room; and (3) pillar stresses will be reduced if some of the initial loads can be transferred to the backfill. If these benefits are proven, positive impacts on other phases of repository design may be realized. For instance, the long-term requirements of seals and plugs may be relaxed, and the closure of rooms by creep deformation may be reduced.

Assessment of the benefits of crushed-salt backfills requires a knowledge of the material properties and behavior. The material properties and behavior of interest are

- Deformation during loading (quasi-static)
- Deformation at constant load (creep)
- Permeability
- Strength.

The quasi-static and creep behavior is important in modeling the response of the backfill to stresses caused by creep deformation of the surrounding rock salt. Permeability and the decrease in permeability with consolidation and time are important to the overall sealing of the repository to limit radionuclide migration. Strength is important as it is an indicator of the relative ease with which the backfill can be mined should retrieval of the waste become necessary. The material properties and behavior can be determined from laboratory or field testing.

Several investigators [Hansen, 1976; Stinebaugh, 1979; Shor et al, 1981; and Holcomb and Hannum, 1982] have studied the behavior of crushed salt in laboratory experiments. A summary [IT Corporation, 1984] of these studies suggests that crushed-salt behavior is affected by several factors or variables, namely:

- Salt impurities
- Grain size
- Grain size distribution
- Initial porosity
- Moisture content
- Stress state
- Load path
- Temperature
- Time.

Most of the past studies examined the effects of only one or perhaps several of the variables on the behavior of crushed salt. The objectives of this study are to determine statistically the main effects of four of these variables and the interactions among these variables relevant to two material properties, consolidation and strength. As a result, successive test matrices can be designed to examine only those variables that significantly affect the behavior of crushed salt.

1.2 APPROACH AND SCOPE

A laboratory experiment was developed using a class of statistical designs commonly known as two-level factorial designs [Box et al, 1978]. In these designs, two levels for each of a number of variables are selected; then, tests are performed with all possible combinations of levels and variables to evaluate the relative effects on a response. In this study, the variables are those given above, and the responses are the ratio of postcreep consolidation bulk density to precreep consolidation bulk density, ρ_f/ρ_i; the ratio of postcreep consolidation bulk density to the original undeformed bulk density, ρ_f/ρ_o; and the unconfined compressive strength, C_o. (Permeability rather than the ratios of bulk densities was the response of interest; however, the measurement of permeability on trial specimens of consolidated crushed salt revealed such large permeabilities that the RE/SPEC permeability apparatus could not be used).

Because of the large number of tests required to include all nine variables in this design ($2^9 = 512$) and because of the limited time and money available, the full factorial design with nine variables was modified to a half-fraction design with four variables; i.e., time, grain size distribution, temperature, and moisture content. The variables and their respective levels are shown in Table 1-1. As a result of this modification, only eight tests were required for the experiment and are shown in Table 1-2.

The variable levels shown in Table 1-1, with the obvious exception of time, were selected to bracket expected levels at a typical salt repository. The 25°C temperature level is representative of temperatures expected in access rooms and at long times; while the 100°C level was selected to represent expected peak backfill temperatures in disposal rooms. The well-graded grain size distribution represented the expected distribution of mined crushed salt with one exception: grains larger than 9.5 mm were removed to stay within acceptable grain size-to-specimen size criterion. The uniform distribution was included as an extreme contrast; however, if results of testing on this material prove favorable, the distribution may become representative of the backfill in future designs. Additionally, the distributions were selected to have identical mean grain sizes to eliminate mean grain size effects. The dry level of moisture content is nearly representative of mine-run ore from a potential repository. The wet level (approximately 3 to 4 percent) was selected as the highest moisture content considered acceptable in an operating repository. Since long times are not practical, a high level was chosen to meet test schedules. The low level was then set to provide a sufficient time difference between levels for valid statistical inference.

In each of the eight tests, a crushed-salt specimen constructed of either uniform-graded or well-graded grain sizes that had been either dried at 105°C or humidified (85 percent relative humidity at 26.5°C) for 24 hours was subjected to a hydrostatic compressive stress of 10 MPa and permitted to consolidate (creep). The consolidation stage was performed at temperatures of either 25°C or 100°C and lasted either 3.5×10^3s or 950×10^3s. Immediately after consolidation, an unconfined compression test was performed at a nominal strain rate of $1 \times 10^{-5}s^{-1}$ and a temperature of 20°C.

Mean values for each response (bulk density ratios and unconfined compressive strength) were determined. In addition, for each response the four main variable effects and three two-variable interactions were calculated. Results show that the mean values for the bulk density ratios (ρ_f/ρ_i and ρ_f/ρ_o) and unconfined compressive strength are 1.08, 1.27, and 9.0 MPa, respectively. The variables that significantly influence the bulk density ratio during creep are time and moisture content; while grain size distribution and, to a somewhat

Table 1-1. Variables and Their Levels in Current Experiment

Variable	Low Level	High Level
Temperature (°C)	25	100
Time[a] (10^3s)	3.5	950
Grain Size Distribution (Based on Coefficient of Uniformity, D_{60}/D_{10})[b]	1	8
Moisture Content[c]	D	W

(a) After stress application.

(b) Ratio of diameters of grains for which 60 percent, D_{60}, and 10 percent, D_{10}, are smaller, respectively. See Table 2-1 and Figure 2-1 for actual size distribution.

(c) D-Dry, stored with desiccant; W-Wet, placed in an 85 percent relative humidity environment for 24 hours.

Table 1-2. Test Matrix for Crushed-Salt Experiment[a]

Run	Temperature (°C)	Time (10^3s)	Grain Size Distribution (D_{60}/D_{10})	Moisture
1	100	950	8	W
2	25	950	8	D
3	100	3.5	8	D
4	25	3.5	8	W
5	100	950	1	D
6	25	950	1	W
7	100	3.5	1	W
8	25	3.5	1	D

(a) All tests performed at a hydrostatic stress of 10 MPa.

lesser degree, temperature have the greatest influence on the bulk density ratio for total consolidation. Strength is significantly influenced by time and moisture content and the two-factor interactions between either grain size distribution and time or temperature and moisture content.

1.3 REPORT ORGANIZATION

The remainder of the report is divided into five chapters and two appendixes. The next chapter describes the specimens used in this study, and the third chapter describes the test machines used and gives the test procedures. Test results are given in the fourth chapter, and the fifth chapter presents an analysis of the data. The sixth chapter gives the conclusions of this study and is followed by a list of cited references. Two appendixes conclude the report. Appendix A gives the volumetric strain-versus-mean stress curves for each of the eight hydrostatic stress applications. Appendix B gives the volumetric strain-versus-time curves for the consolidation stages of the eight tests.

2 SPECIMENS

2.1 SALT CRUSHING AND SIZING

The crushed salt for this experiment was fabricated by passing intact salt core fragments from the Avery Island Mine in Louisiana through a conventional flour mill. The mill, equipped with a set of adjustable grinding stones, permits a selection of aperture settings appropriate for the grain sizes required in the current study. After the salt was crushed, it was dried in a conventional oven at 105°C for 24 hours. To obtain grains of nominally equal size, the dried crushed salt was separated using a series of U.S. Standard Sieves. The sieves used in this procedure and their respective size of openings are given in Table 2-1. The uniform grains retained on each sieve were stored with a $CaSO_4$ desiccant in jars until sufficient quantities of all grain sizes were obtained.

Accurate ratios of each uniform grain size were blended to form two distributions: one, a well-graded (WG) distribution having a coefficient of uniformity*, C_u, of 8; and the second, an extremely uniform-graded (UG) distribution with $C_u = 1$. The grain size distribution for each blend is given in Table 2-1, and the curve is shown in Figure 2-1. Both distributions have an average grain size of 1 mm. The maximum and minimum sizes for the well-graded distribution are 9.5 mm and 0.075 mm, respectively, and for the uniform-graded distribution are 1.18 mm and 0.850 mm, respectively. Each distribution was stored with desiccant in jars until required for the experiment.

2.2 SPECIMEN PREPARATION

The specimens for each test were prepared identically in all cases. A portion of crushed salt was removed from a desiccator jar and accurately weighed (0.27 kg for the uniform-graded distribution and 0.36 kg for the well-graded distribution) with a Mettler P1200N balance having a resolution of 0.01 g. If the specimen required wetting, the crushed salt was placed in a shallow dish

* The coefficient of uniformity, C_u, is defined as the ratio of the grain diameter at the 60 percent passing point to that at the 10 percent passing point on the gradation curve, or $C_u = D_{60}/D_{10}$.

Table 2-1. Sieve Stack and Grain Size Distributions for Crushed-Salt Experiment

Sieve No.[a]	Sieve Size (mm)	Distribution - Percent Passing	
		Uniform Graded	Well Graded
3/8 in	9.500	-	100
5/16 in	8.000	-	98
3	6.300	-	96
4	4.750	-	91
5	4.000	-	87.5
6	3.350	-	84
7	2.800	-	80
8	2.360	-	75
10	2.000	-	70
12	1.700	-	65
14	1.400	-	60
16	1.180	100	54
18	1.000	50	50
20	0.850	0	44
30	0.600	-	34
40	0.425	-	26
60	0.250	-	15
140	0.106	-	3
200	0.075	-	0

(a) U.S. Standard Sieves conforming to American Society for Testing and Materials (ASTM) Specification E11.

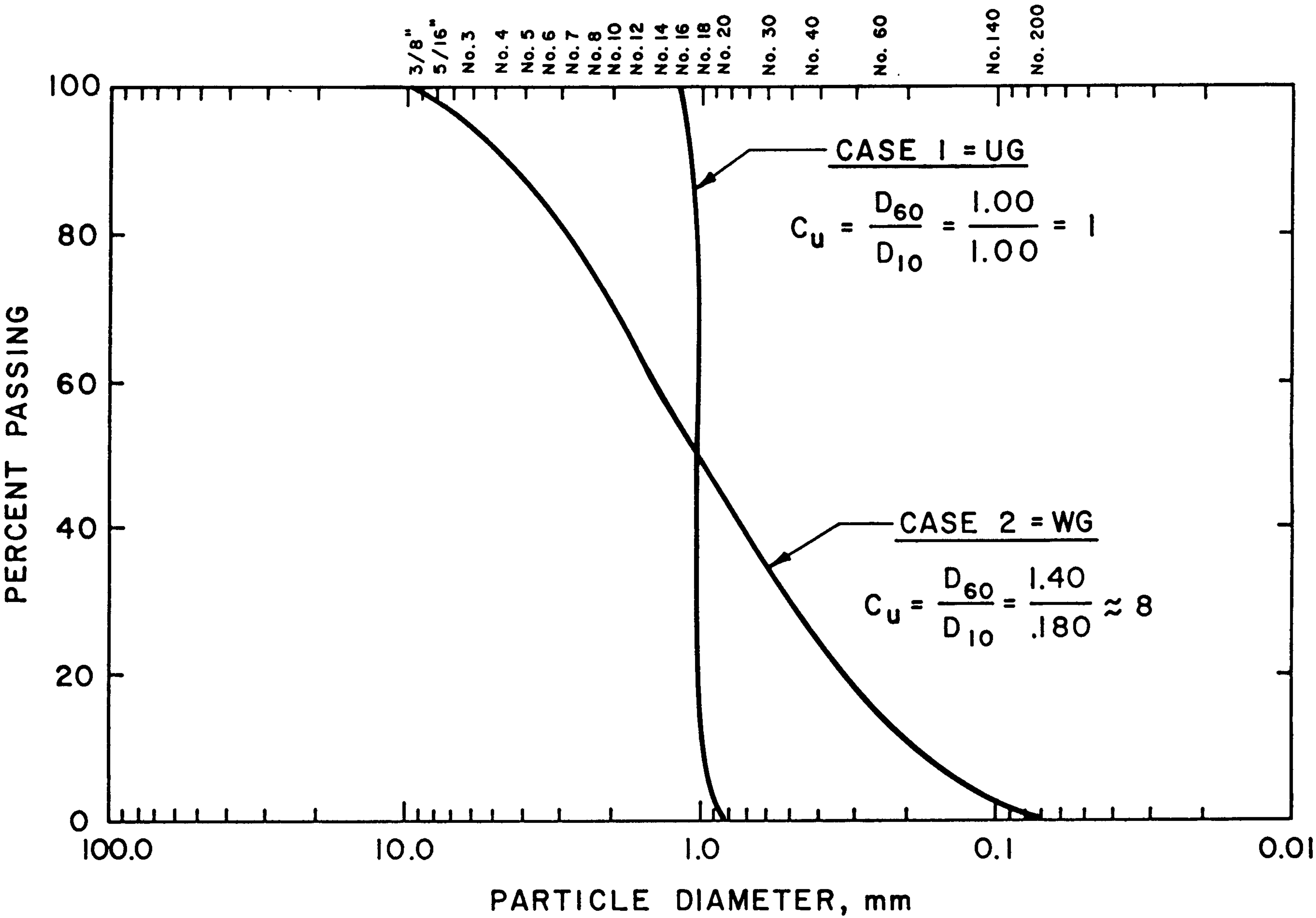

Figure 2-1. Particle Size Distribution Curves for Crushed-Salt Experiment

that was then placed in a humidity chamber for 24 hours at 85 percent relative humidity and 26.5°C. Upon removal from the chamber, the crushed salt was again weighed to determine the free moisture content. The moisture content of the wet salt was 3 to 4 percent by weight and does not include any water initially present either within crystals or on grain boundaries. The specimen was fabricated by compacting three equal layers of crushed salt in a Viton jacket and mold affixed to a steel load platen as shown in Figure 2-2. The compactive effort for each layer was 494 $kJ \cdot m^{-3}$ and was attained by 25 repetitions of a 0.9-kg hammer free-falling from a height of 0.15 m. (Various combinations of repetitions, hammer weight, and height were used on trial specimens to obtain the highest initial density possible without significant crushing of individual grains.) A steel load platen was placed on the top of the compacted specimen, and the Viton jacket was secured to this upper platen with lock wire.

The initial dimensions of each specimen were determined indirectly following compaction. The length was determined by measuring the total length of the specimen-platen assembly and subtracting the combined lengths of the platens. The diameter was determined by subtracting two thicknesses of the Viton jacket from the inside diameter of the mold. Nominal dimensions for all specimens were 50-mm diameters by 100-mm lengths. Each specimen was assigned an identification number and logged into the RE/SPEC computerized core inventory. A typical identification number is

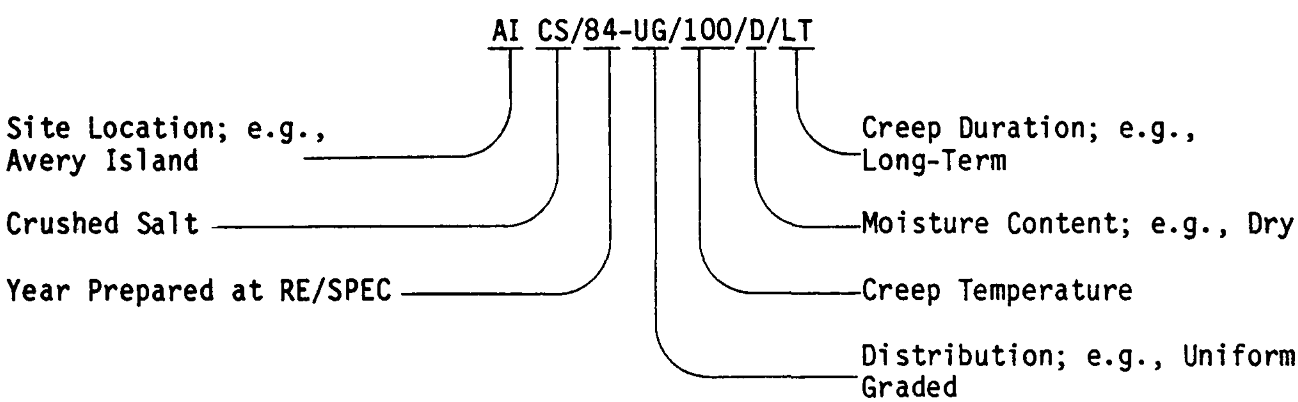

Table 2-2 summarizes the initial dimensions and conditions for each specimen.

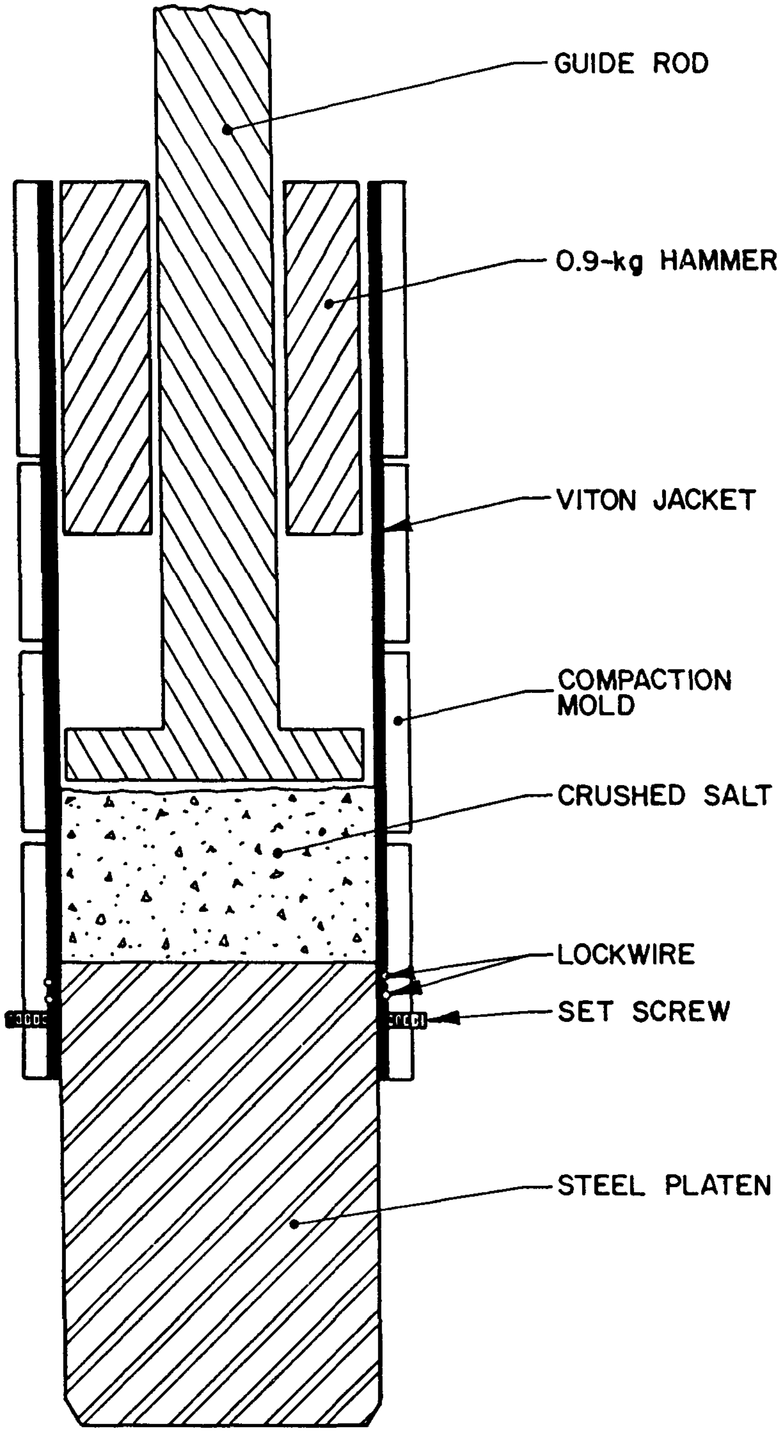

Figure 2-2. Crushed-Salt Compaction Mold and Hammer

Table 2-2. Summary of Initial Specimen Dimensions and Conditions

Specimen I.D.	Length (mm)	Diameter (mm)	Weight (kg)	Density Dry, ρ_0 (kg/m^3)	Porosity[a]	Moisture[b] Content (%)
AICS/84-WG/100/W/LT	109.6	51.2	0.36	1595	0.27	3.2
AICS/84-WG/25/D/LT	105.5	51.2	0.36	1660	0.24	-
AICS/84-WG/100/D/ST	107.9	51.2	0.36	1620	0.26	-
AICS/84-WG/25/W/ST	108.4	51.2	0.36	1615	0.26	3.3
AICS/84-UG/100/D/LT	100.0	51.2	0.27	1310	0.40	-
AICS/84-UG/25/W/LT	101.6	51.2	0.27	1290	0.41	4.3
AICS/84-UG/100/W/ST	104.4	51.2	0.27	1255	0.43	4.3
AICS/84-UG/25/D/ST	104.5	51.2	0.27	1255	0.43	-

(a) Assumes a theoretical salt density of 2190 kg/m^3.

(b) Based on dry weight.

2.3 POST-TEST DISPOSITION

After each specimen has been tested, it is sealed in a plastic bag with an identification tag and stored in the RE/SPEC core facilities. An inventory record of specimens is also kept in the RE/SPEC offices.

3 TESTING

The hydrostatic consolidation tests were conducted using two triaxial machines. The machines were designed and constructed by Dr. W. R. Wawersik of Sandia National Laboratories. These machines have been described in a previous publication [Hansen and Mellegard, 1980] and have the distinctive capability of measuring volumetric changes during a hydrostatic consolidation creep test. The unconfined compression tests were conducted using a computer-controlled, universal load frame designed by MTS Systems Corporation.

3.1 LOAD FRAMES

3.1.1 Consolidation Machines

Figure 3-1 presents a cross section of a typical load frame for hydrostatic consolidation creep testing with prominent components labeled for reference. The machines use a double-ended, triaxial pressure vessel that accommodates a 50-mm-diameter cylindrical specimen having a length-to-diameter ratio of L:D = 2. A hydraulic cylinder bolted on the load frame drives the loading piston, which applies axial compressive force to the specimen. Confining pressure is applied to the jacketed specimen by pressurizing the sealed vessel chamber with silicone oil. A dilatometer system maintains constant confining pressure and provides volumetric measurements.

The two testing machines can apply confining pressures up to 70 MPa. One machine can apply a compressive axial load up to 270 kN, while the other has a greater axial load capability and can apply a load up to 530 kN. The heating system, including seals on the pressure vessel, can maintain specimen temperatures up to 200°C.

The test frame and control panel house the accumulators, hydraulic pumps, pressure intensifiers, temperature controllers, and confining pressure controllers for both test frames. The panels contain digital meters that display the output of the transducers. The temperature controller gives a digital output of the temperature. Mechanical pressure gages give readings of the nitrogen pressure in the accumulator and the oil pressure in the hydraulic cylinder.

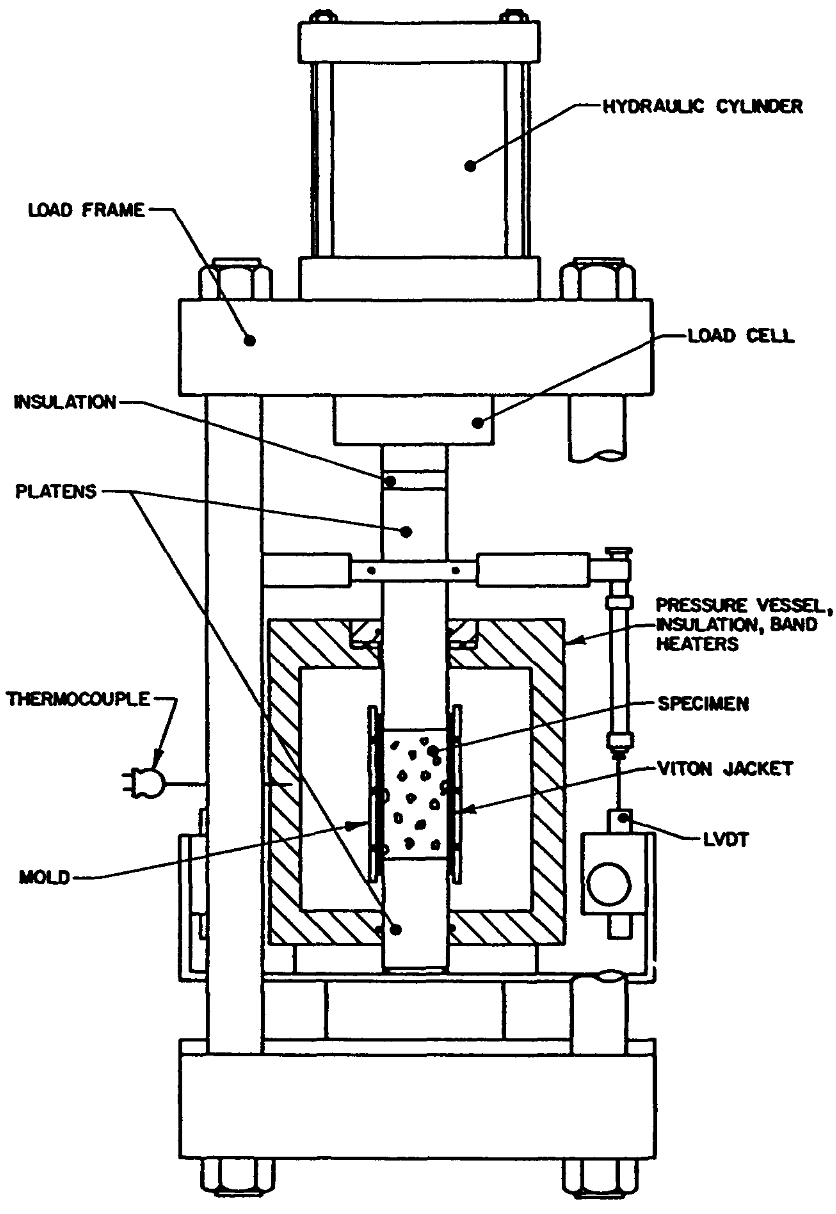

Figure 3-1. Creep Test Machine Schematic

3.1.2 MTS Universal Load Frame

Figure 3-2 presents the characteristic two-post design of the MTS universal load frame. A hydraulic cylinder located in the base of the machine can apply 500 kN of force (tensile/compressive) to a specimen. The movable crosshead allows for a wide range of specimen lengths.

The machine is completely servocontrolled. A Digital Equipment Corporation (DEC) LSI-11/23 microcomputer (programmable in BASIC) provides closed loop test control in either load or displacement feedback mode.

3.2 INSTRUMENTATION

3.2.1 Consolidation Machines

Axial force is measured by a load cell in the load train outside the pressure vessel, while confining pressure is measured by a pressure transducer in the line between the intensifier and the pressure vessel. Temperature is measured by a thermocouple in the wall of the pressure vessel. The relationship between specimen temperature and that recorded by this thermocouple has been determined by calibration runs at several temperatures that span the operating range. Axial deformation in the specimen is measured by two Linear Variable Differential Transformers (LVDTs) mounted outside the pressure vessel. They monitor displacement of the loading piston relative to the bottom of the pressure vessel. Lateral deformation is measured using a dilatometer. With this technique, lateral deformation is determined at fixed pressure by measuring the volume of oil that the intensifier replaces in the pressure vessel, and then compensating for the axial deformation measured by the LVDTs. A rotary potentiometer is mounted on the intensifier shaft to provide a signal that is proportional to the volume of oil that is replaced in the pressure vessel.

Data collected consist of axial force, confining pressure, axial displacement, volumetric displacement, and temperature. A COMTEL Corporation DATAC 600 System and a Data General Corporation NOVA 2 minicomputer provide control for logging data and converting transducer signals to engineering units.

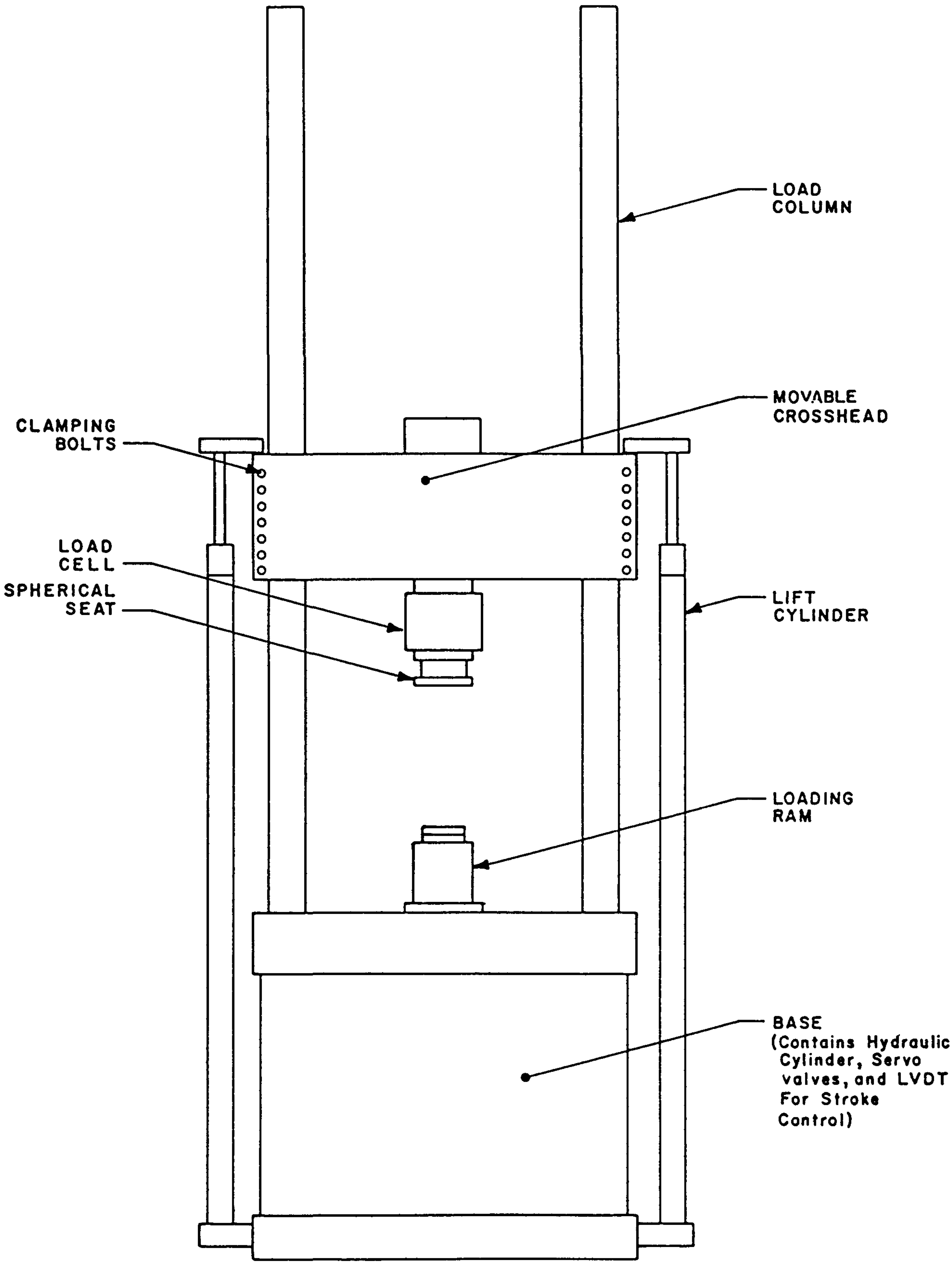

Figure 3-2. MTS Universal Load Frame

3.2.2 MTS Universal Load Frame

Only axial force was measured in the unconfined compression tests and is measured by a load cell equipped with a spherical seat. A control console houses the signal conditioning for the transducer and interfaces with a DEC LSI-11/23 microcomputer to provide data acquisition.

3.3 CALIBRATION

The transducers used to collect data are calibrated using standards traceable to the National Bureau of Standards. Table 3-1 summarizes the results of the calibration.

3.4 CONTROL

3.4.1 Consolidation Machines

Temperature is controlled with a controller having a manual set point that regulates power to the band heaters on the vessel. The thermocouple in the pressure vessel wall supplies the feedback signal. The specimen temperature is maintained constant within 0.2°C. Confining pressure is controlled by inputting the pressure transducer signal to a unit that contains two manual set points. These set points are adjusted to maintain the confining pressure constant within 20 kPa. When a set point is reached, the controller signals the intensifier to advance or retreat, depending upon whether the lower or upper set point has been reached. Axial load is controlled manually by metering gas into or out of a nitrogen-charged bladder accumulator. The deadband on load is 1.0 kN, and for 50-mm-diameter specimens, gives a deadband on axial stress of 0.50 MPa.

3.4.2 MTS Universal Load Frame

The unconfined compression tests require only the control of the axial strain rate. Programmable control of the strain rate is provided by an LVDT mounted in the load actuator at the base of the load frame, a control console housing feedback and valve driver modules for the hydraulics, and a DEC LSI-11/23 microcomputer.

Table 3-1. Calibration Results

Measurement	Range	Accuracy	Resolution
CONSOLIDATION MACHINES			
Axial Strain (Percent)	0-25	0.125	0.0025
Lateral Strain (Percent)	0- 5	0.01[a]	0.0004[a]
Axial Load (kN)			
Machine 1	0-530	0.75	0.05
Machine 2	0-270	0.95	0.03
Confining Pressure (MPa)	0- 70	0.04	0.007
Temperature (°C)	25-200	2.0[b]	0.02
MTS UNIVERSAL LOAD FRAME			
Axial Load (kN)	0- 50	0.05	0.01[c]

(a) Accuracy and resolution determined at zero strain.

(b) Manufacturer's specified accuracy.

(c) 14-bit analog-to-digital converter with one bit to denote sign.

3.5 TEST PROCEDURES

3.5.1 Consolidation Tests

Consolidation tests are performed in two stages. In the first stage, hydrostatic stress is applied quasi-statically until the target stress is reached. This is followed by the second stage, the creep stage, in which consolidation occurs with time. The discussion below describes the procedure for both stages.

Jacketed specimens of crushed salt are placed in a pressure vessel that is subsequently filled with silicone oil. The vessel is sealed and placed in a load frame. The specimen is heated to the target temperature and allowed to stabilize for 12 hours. Following stabilization, a hydrostatic stress is applied by the operator. Since the vessel design features axial and confining pressure hydraulics that are decoupled, the hydrostatic stress application is performed quasi-statically by increasing the confining pressure while simultaneously applying an axial force. Pressure increments of 0.5 MPa are used to prevent large deviatoric stresses. The stress application stage requires about 20 minutes to complete, resulting in a nominal load rate of $1 \times 10^{-2} \mathrm{MPa \cdot s^{-1}}$. When the target hydrostatic creep stress of 10 MPa is reached, the dilatometer servosystem is actuated to maintain constant confining pressure. Axial load is maintained during the creep stage with a nitrogen-charged accumulator. Adjustment of the load is made periodically by the operator by either adding nitrogen to or venting nitrogen from the accumulator. During the test, data are logged according to one of two criteria. First, if the specimen length changes by a prescribed amount since the last data were logged, data are logged again. If, however, the specimen length changes by less than the prescribed amount over a time selected by the operator, data are logged at the end of this time period. When the desired creep duration is reached, the hydrostatic stress is removed in decrements of 0.5 MPa at a rate of $1 \times 10^{-2} \mathrm{MPa \cdot s^{-1}}$.

3.5.2 Unconfined Compression Tests

Each consolidated specimen is placed in the MTS universal load frame immediately after removal from the pressure vessel. In load control, a small preload is applied to the specimen. The control program is initiated by the operator and requires input of the specimen dimensions. Control is then switched to the stroke transducer (LVDT), and the specimen is loaded at a nominal axial strain rate of $1 \times 10^{-5} s^{-1}$ to failure. The computer identifies failure as a 10 percent decrease in load below the peak load carried by the specimen. Control is switched back to the load cell, and the specimen is quickly unloaded. The unconfined compressive strength is calculated from the post-consolidation specimen dimensions and the peak load and is printed at the control terminal.

4 RESULTS

4.1 CONSOLIDATION TESTS

4.1.1 Quasi-Static Behavior

The quasi-static volumetric strain data are used to determine the initial density of each specimen before creep consolidation occurs by

$$\rho_i = \frac{\rho_o}{1 - \varepsilon_v} \qquad (4\text{-}1)$$

where ρ_i and ρ_o are the initial density before creep and the original undeformed specimen density (Table 2-2), respectively, and ε_v is the volumetric strain that occurred during quasi-static application of the hydrostatic load. Table 4-1 gives the original density and initial density for each specimen as calculated from Equation 4-1. The volumetric strain, ε_v, can be related to the principal engineering strains, ε_1 and ε_2, by

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_2 + \varepsilon_1\varepsilon_2^2 - 2\varepsilon_1\varepsilon_2 - \varepsilon_2^2 \qquad (4\text{-}2)$$

Equation 4-2 assumes that $\varepsilon_2 = \varepsilon_3$ (true for traditional triaxial test equipment) and includes second and third order terms important in large-strain determination. For true hydrostatic loading assuming material isotropy, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3$. Thus, Equation 4-2 can be rewritten as

$$\varepsilon_v = 3\varepsilon_1 + \varepsilon_1^3 - 3\varepsilon_1^2 \qquad (4\text{-}3)$$

and only ε_1 (i.e., the axial strain which is equal to the change in specimen length, ΔL, divided by the original specimen length, L_o) needs to be measured. The isotropy assumption will be discussed in the next section.

Plots of quasi-static volumetric strain as calculated from Equation 4-3 versus mean stress for each test are given in Appendix A. Mean stress is calculated simply by

Table 4-1. Summary of Results for the Crushed-Salt Experiment

Specimen I.D.	Specimen Density Original, ρ_o (kg/m^3)	Specimen Density Prior to Creep, ρ_i (kg/m^3)	Specimen Density After Creep, ρ_f (kg/m^3)	ρ_f / ρ_i	ρ_f / ρ_o	Unconfined Compressive Strength, C_o (MPa)
AICS/84-WG/100/W/LT	1595	1800	2085	1.16	1.31	30.1
AICS/84-WG/25/D/LT	1660	1785	1820	1.02	1.10	7.9
AICS/84-WG/100/D/ST	1620	1820	1850	1.02	1.14	0.0
AICS/84-WG/25/W/ST	1615	1790	1845	1.03	1.14	2.0
AICS/84-UG/100/D/LT	1310	1695	1940	1.14	1.48	8.3
AICS/84-UG/25/W/LT	1290	1525	1775	1.16	1.38	9.9
AICS/84-UG/100/W/ST	1255	1620	1765	1.09	1.41	8.2
AICS/84-UG/25/D/ST	1255	1490	1520	1.02	1.21	5.3

$$\sigma_m = \frac{\sigma_1 + 2\sigma_2}{3} \tag{4-4}$$

where σ_1 and σ_2 are the axial stress and confining pressure, respectively. For comparative purposes, the volumetric strain-versus-mean stress curves are plotted in Figure 4-1. It is apparent, at least qualitatively, that larger volumetric strains occur at the high level of temperature (i.e., 100°C) and at the low level of grain size distribution (i.e., $C_u = 1$).

4.1.2 Creep

During the creep stage, the lateral strain, ε_2, is determined directly from volume measurements of oil replaced in the vessel by

$$\varepsilon_2 = 1 - \sqrt{1 - \frac{1}{(L_i - \Delta L)D_i^2} \left\{\frac{4\Delta V}{\pi} + \Delta L\,(D_p^2 - D_i^2)\right\}} \tag{4-5}$$

where

ε_2 = Lateral engineering strain, $\Delta D/D_i$

L_i, D_i = Initial specimen length and diameter before creep

ΔL = Change in specimen length

ΔV = Volume of oil replaced in the vessel corrected for temperature

D_p = Diameter of the loading platen

The validity of the isotropy assumption in the previous section can be checked by comparing the volumetric strains as calculated using Equation 4-3 and those calculated using Equation 4-2. If the assumption is correct, both equations should yield identical volumetric strains. Appendix B gives plots of volumetric creep strain using both equations for each of the eight tests. In general, the agreement between the two equations is good, thereby validating the assumption of isotropy.

Figures 4-2 and 4-3 give plots of volumetric creep strain (Equation 4-2) for the short- and long-term tests, respectively. The main effects of the

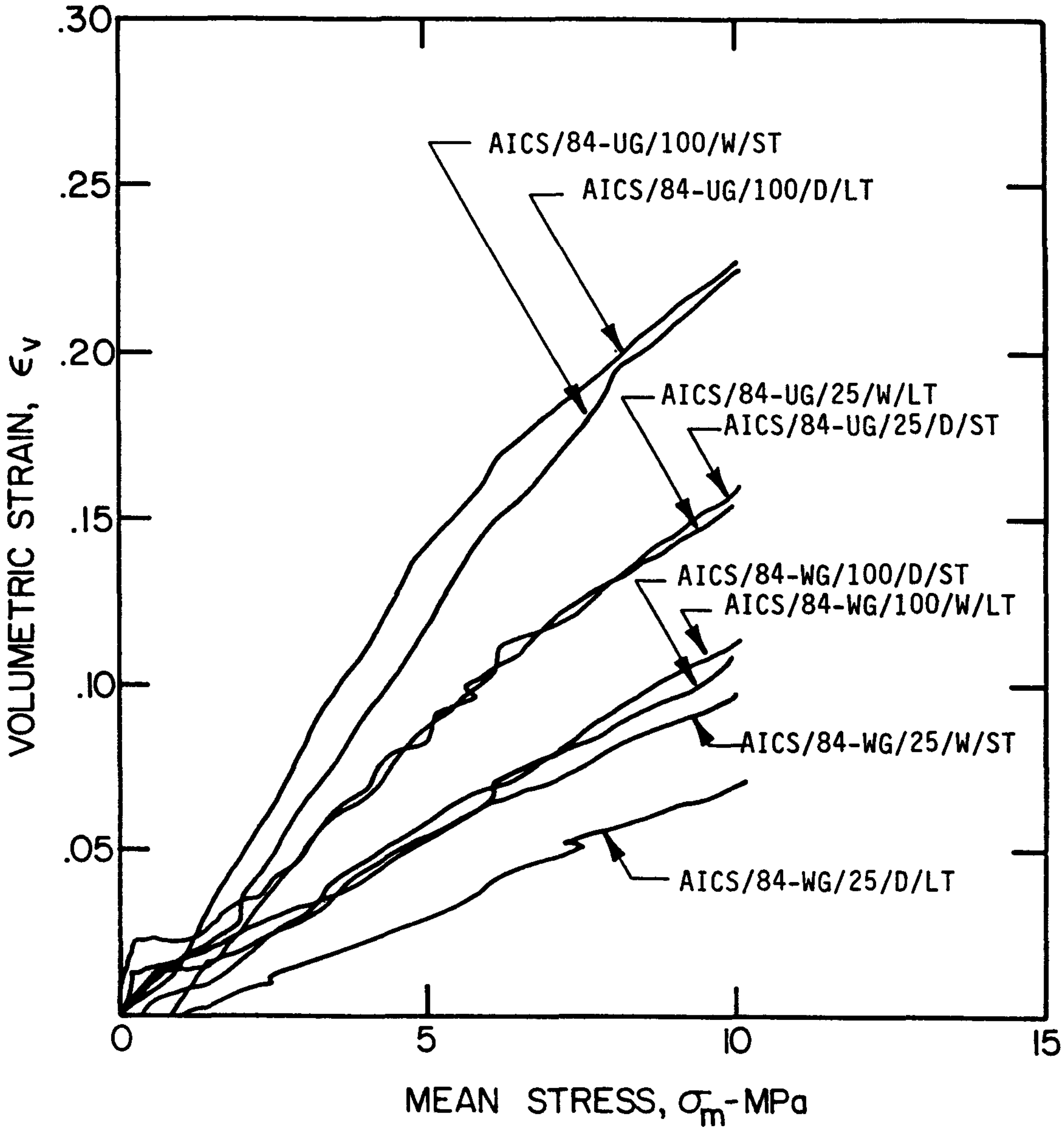

Figure 4-1. Volumetric Strain-Versus-Mean Stress for Avery Island Crushed Salt

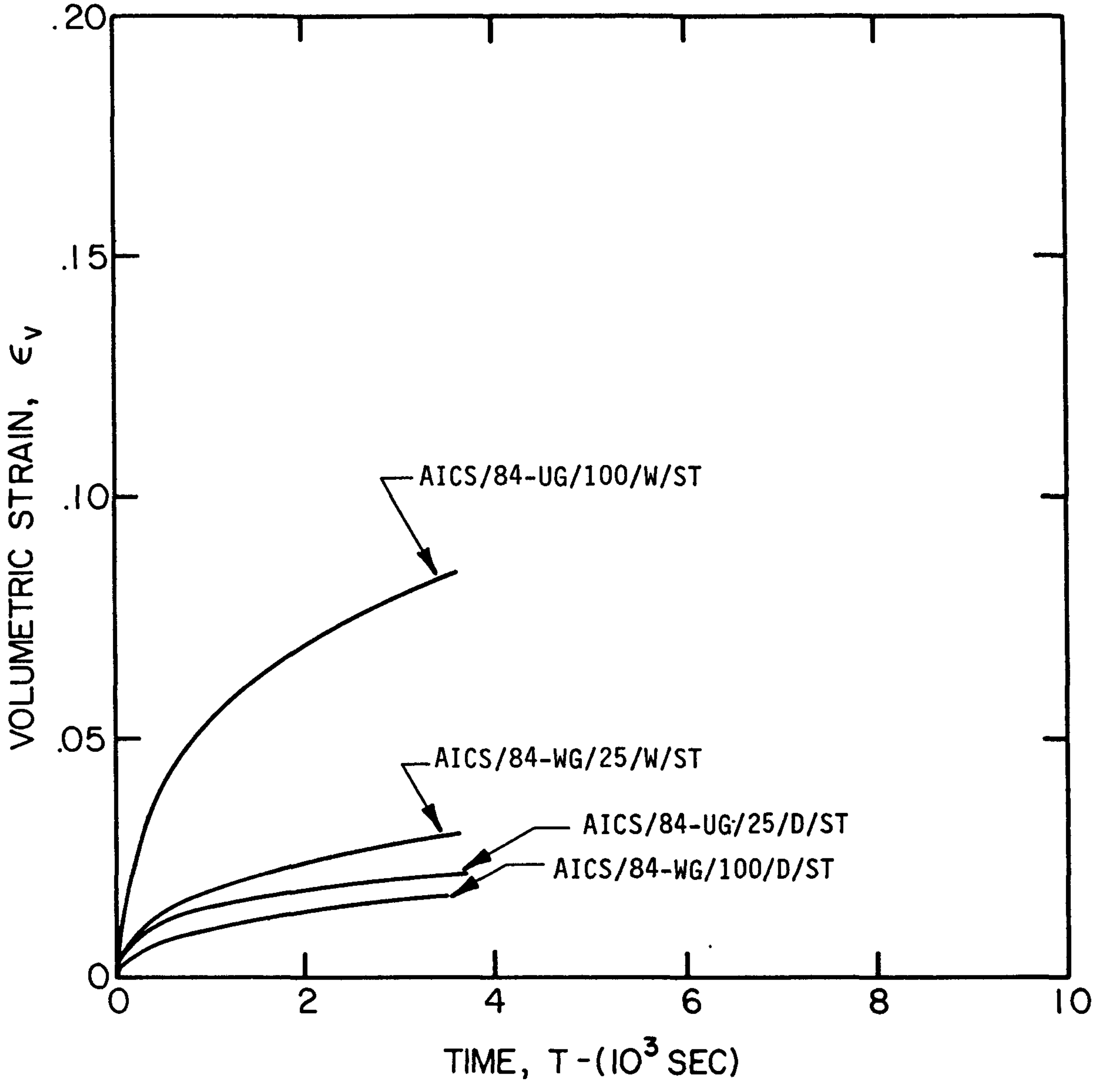

Figure 4-2. Volumetric Creep Strain for Avery Island Crushed Salt at the Low Level of the Variable, Time

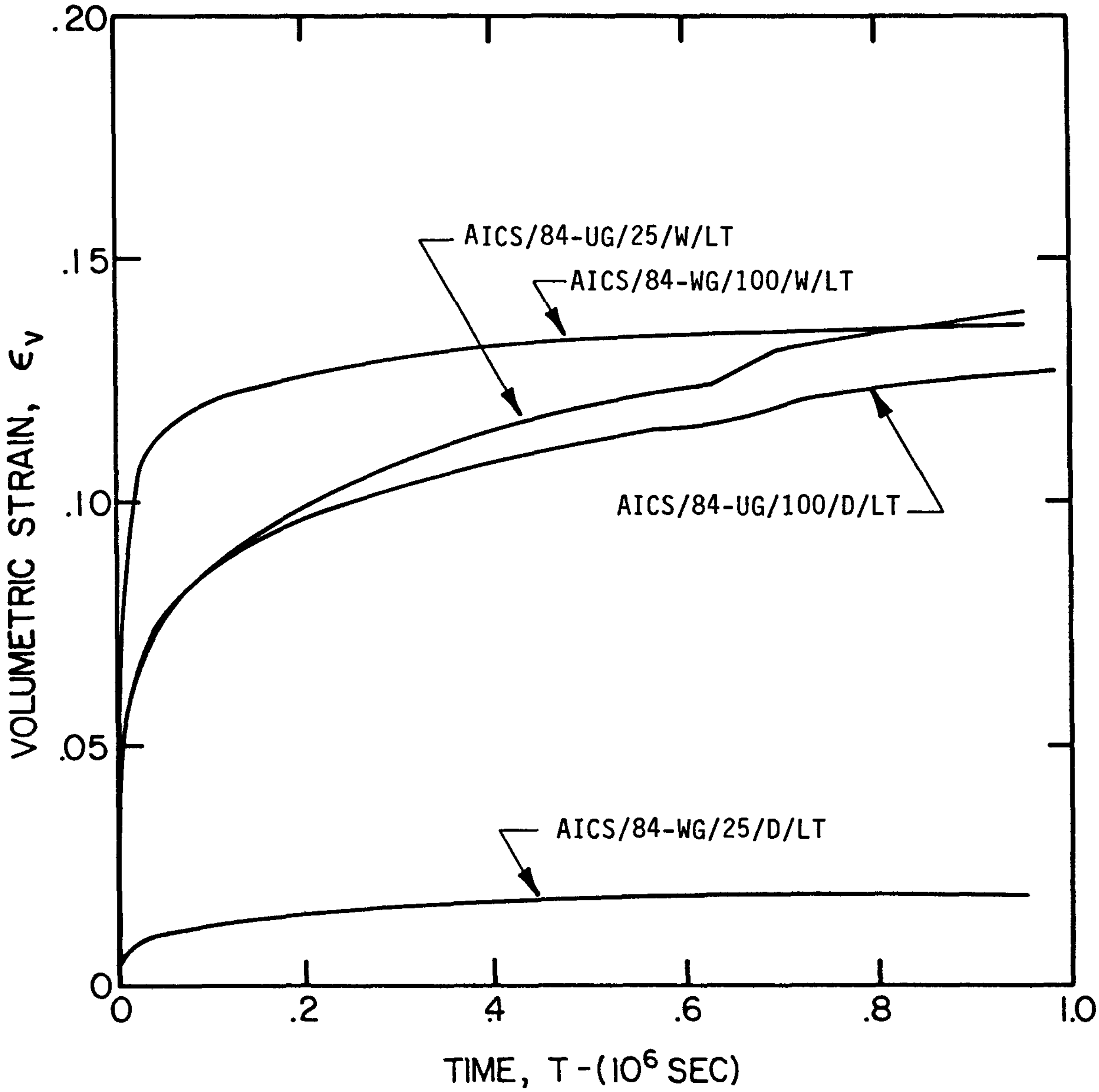

Figure 4-3. Volumetric Creep Strain for Avery Island Crushed Salt at the High Level of the Variable, Time

variables are not as clear as before, and variable interactions are probably more important. The density, ρ_f, is determined after the creep stage using Equations 4-1 and 4-2 and substituting ρ_f for ρ_i, ρ_i for ρ_o, and the volumetric creep strain for ε_v. The final density for each specimen and the ratios ρ_f/ρ_i and ρ_f/ρ_o are given in Table 4-1. These final densities agree well with density measurements made after the specimens are removed from the pressure vessel. It should also be noted from Table 4-1 and the appendixes that most of the consolidation occurs during the application of hydrostatic load.

4.2 UNCONFINED COMPRESSION TESTS

The results of the unconfined compression tests are also given in Table 4-1. The values of C_o are based on the dimensions of the specimen after consolidation and are not corrected for shape change during the unconfined test. All values are below 10 MPa with the exception of one value (30.1 MPa) determined for the wet, well-graded specimen consolidated at 100°C, long term. This value is higher than the average value (23.1 MPa) reported by Hansen and Mellegard [1980] for intact Avery Island salt.

5 ANALYSIS

5.1 DISCUSSION

The number of runs required by a full factorial design at two levels increases geometrically with the number of variables or factors to be studied. For instance, if the influence of nine variables is to be assessed, as is the case for crushed salt, $2^9 = 512$ runs or tests would be required. From these runs, 512 statistics could be calculated which estimate main effects, as well as interaction effects. In an effort to save both time and money and because full factorial designs tend to be inherently redundant, a half-fraction factorial design approach [Box et al, 1978] considering only four variables; i.e., grain size distribution, temperature, time, and moisture content, was used to analyze the results presented in the previous section. Although no information is obtained for the other five variables (i.e., impurities, grain size, initial porosity, stress state, and load path), any of these variables can be added at a later time without affecting the design or analysis. In addition, if variables currently under study have no distinguishable effect, they can be deleted in subsequent experiments.

A half-fraction for four variables requires eight runs or tests. The eight runs are chosen by writing a full factorial design for the first three variables (in this case, grain size distribution, temperature, and moisture content) using minus and plus signs to denote the low and high levels of each variable, respectively. Table 5-1 shows the signs for the first three variables in Columns 1 through 3. The level of the remaining variable, time, is selected for each run by determining the sign of the algebraic product of the signs in the first three columns in Table 5-1. For instance in run one, the sign of the algebraic product is positive; i.e., (+) = (+) x (+) x (+), and thus, the high level (950×10^3s) for the variable, time, is required for run one. Column 4 gives the signs for the remaining runs.

The half fraction can also be designated by 2^{4-1}_{IV}: the notation implies that four variables at two levels are considered, but that only $2^{4-1} = 8$ runs are employed. The subscript IV gives the resolution of the design and indicates the confounding pattern. Confounding occurs when all the runs of a full factorial are not performed. To define the confounding pattern, Table 5-1 is used and three-factor and higher order interactions are assumed to be negligible. Product columns of plus and minus signs are determined for each

Table 5-1. Sign Convention Used in the Current Study to Estimate the Variable Effects

Run	Design Variable				Variable Interactions			Response		
	Grain Size Distribution (1)	Temperature (2)	Moisture Content (3)	Time (4)	1 x 2 = 3 x 4 (5)	1 x 3 = 2 x 4 (6)	1 x 4 = 2 x 3 (7)	ρ_f/ρ_i (8)	ρ_f/ρ_o (9)	C_o (MPa) (10)
1	+	+	+	+	+	+	+	1.16	1.31	30.1
2	+	-	-	+	-	-	+	1.02	1.10	7.9
3	+	+	-	-	+	-	-	1.02	1.14	0.0
4	+	-	+	-	-	+	-	1.03	1.14	2.0
5	-	+	-	+	-	+	-	1.14	1.48	8.3
6	-	-	+	+	+	-	-	1.16	1.38	9.9
7	-	+	+	-	-	-	+	1.09	1.41	8.2
8	-	-	-	-	+	+	+	1.02	1.21	5.3

two-factor interaction by multiplication of the individual elements of the columns for the two factors (variables) to be studied. For example, the signs in Column 5; i.e., the interaction between grain size distribution and temperature, are determined by multiplying the elements in Columns 1 and 2. If this is done for all interactions, one sees that the sign sequence in the product columns for 1 x 2 is equal to 3 x 4, 1 x 3 is equal to 2 x 4, and 1 x 4 is equal to 2 x 3. This means these interaction effects are confounded or are alias of one another. If one of these interactions, such as the interaction between grain size distribution and temperature, is found to be important, then the only conclusion one can reach is that either the interaction between grain size distribution and temperature or the interaction between moisture content and time has influence on the response. Thus, the interactions must be considered together and not separately. Table 5-2 shows the alias pattern for the two-factor interactions of this study. In general for a design of resolution IV, main effects and two-factor interactions are not confounded; but two-factor interactions are confounded with other two-factor interactions.

Eight statistics can be calculated for each response measured in the experiment. The statistics are

- One mean
- Four main effects
- Three two-factor interactions.

The mean response is calculated by summing the values in Columns 8, 9, and 10, respectively, and dividing by the number of runs; i.e., eight. The main effects and the two-factor interactions are calculated by algebraically summing the values in Columns 8, 9, and 10, respectively, using the signs in the product Columns 1 through 7 and dividing by the number of runs divided by two; i.e., four. For example, the main effect of grain size distribution on the creep consolidation bulk density ratio, ρ_f/ρ_i, is -0.045 and is calculated from

$$-0.045 = \frac{\{+\ 1.16 + 1.02 + 1.02 + 1.03 - 1.14 - 1.16 - 1.09 - 1.02\}}{4} \qquad (5\text{-}1)$$

The statistics for each response are presented below.

Table 5-2. Alias Pattern for the 2_{IV}^{4-1} Experiment

Two-Factor Interaction	Alias
Grain Size Distribution x Temperature	Moisture Content x Time
Grain Size Distribution x Moisture Content	Temperature x Time
Grain Size Distribution x Time	Temperature x Moisture Content

5.2 BULK DENSITY RATIO FOR CREEP CONSOLIDATION

The influence of the four variables on the creep consolidation bulk density ratio, ρ_f/ρ_i, is shown in Table 5-3 in terms of the eight statistics. The relative magnitude and not the sign or absolute magnitude is important. The effect of the variable, time, is the most important and is about twice that of either grain size distribution or temperature. Moisture content does have some influence on the consolidation but not quite as much as time. All two-factor interaction effects are only one-fourth to one-third the main effects and as such are insignificant. It is not surprising that the consolidation is influenced by time, since consolidation (or creep) implies time dependence. It should be noted, however, that factorial designs assume linearity between levels. A review of the plots in Appendix B suggests that the volumetric creep strain is not linear. If the levels of time are changed, time may lose its relative influence on consolidation. The relatively insignificant influence of temperature has been documented by others [Hansen, 1976; Holcomb and Hannum, 1982].

5.3 BULK DENSITY RATIO FOR TOTAL CONSOLIDATION

Table 5-4 gives the relative influence of the four variables on the total consolidation bulk density ratio, ρ_f/ρ_o. Grain size distribution and temperature, to a somewhat lesser degree, are the variables with the greatest influence on ρ_f/ρ_o. This result was seen, at least qualitatively, in Figure 4-1. The relatively large influence of grain size distribution is plausible since the uniform-graded distribution starts at a much lower density initially and, therefore, has the potential for greater change in density. This response and the variables that affect it are pertinent to permeability, since they include all consolidation. It is interesting to note the change in the relative importance of the variables when comparing the creep consolidation with the total consolidation. Grain size distribution and temperature are less influential during creep.

5.4 UNCONFINED COMPRESSIVE STRENGTH

Table 5-5 gives the relative influence of the four variables on the unconfined compressive strength in terms of the eight statistics. As with creep,

Table 5-3. Estimate[a] of Variable Effects on the Creep Consolidation Bulk Density Ratio

Statistic	Estimate
Mean	1.080
Main Effects	
Grain Size Distribution	-0.045
Temperature	0.045
Moisture Content	0.060
Time	0.080
Interactions	
Grain Size Distribution x Temperature (Moisture Content x Time)	0.020
Grain Size Distribution x Moisture Content (Temperature x Time)	0.015
Grain Size Distribution x Time (Temperature x Moisture Content)	-0.015

(a) Based on 2^{4-1}_{IV}.

Table 5-4. Estimate[a] of Variable Effects on the Total Consolidation Bulk Density Ratio

Statistic	Estimate
Mean	1.2700
Main Effects	
Grain Size Distribution	-0.1975
Temperature	0.1275
Moisture Content	0.0775
Time	0.0925
Interactions	
Grain Size Distribution x Temperature (Moisture Content x Time)	-0.0225
Grain Size Distribution x Moisture Content (Temperature x Time)	0.0275
Grain Size Distribution x Time (Temperature x Moisture Content)	-0.0275

(a) Based on 2_{IV}^{4-1}.

Table 5-5. Estimate[a] of Variable Effects on Unconfined Strength

Statistic	Estimate
Mean	9.0 MPa
Main Effects	
Grain Size Distribution	2.1
Temperature	5.4
Moisture Content	7.2
Time	10.2
Interactions	
Grain Size Distribution x Temperature (Moisture Content x Time)	4.7
Grain Size Distribution x Moisture Content (Temperature x Time)	4.9
Grain Size Distribution x Time (Temperature x Moisture Content)	7.8

(a) Based on 2_{IV}^{4-1}.

time and moisture content have the greater influence; however, the two-factor interactions between either grain size distribution and time or temperature and moisture content (from Table 5-2 alias pattern) are also of relatively large importance. In fact, each two-factor interaction is more important or as important as the main effects of grain size distribution and temperature.

6 CONCLUSIONS

An experiment has been performed on crushed salt from Avery Island, Louisiana, to assess the influence of four variables on the consolidation and unconfined compressive strength of crushed salt. The four variables studied were grain size distribution, temperature, time, and moisture content. A matrix of eight tests was designed using a half-fraction factorial at two levels. The two levels for each variable were grain size distribution, C_u = 1 and 8; temperature, 25°C and 100°C; time, 3.5 x 10^3s and 950 x 10^3s; and moisture content, dry and wet (85 percent relative humidity at 26.5°C for 24 hours).

An analysis of the results shows that time, and to a somewhat lesser degree, moisture content have the largest influence on the creep consolidation bulk density ratio. Grain size distribution and temperature have the largest influence on the bulk density ratio during the total consolidation. Time and moisture content have the largest influence on the unconfined compressive strength; and in addition, the two-factor interactions between either grain size distribution and time or temperature and moisture content have a relatively significant effect.

The results obtained from this study should be considered when future experimental crushed salt matrices are designed. The confounded effects between grain size distribution and time and temperature and moisture content should be resolved for the unconfined compressive strength. The confounded effects could be eliminated by either performing the remaining eight runs for a full factorial design or choosing a smaller number of additional runs that when performed resolve the ambiguity. Future studies should retain the four current variables and incorporate new variables to determine their relative significance. Additionally, future experiments should include replication so that data variability can be estimated. Model building can begin when significant variables are identified and should reflect other levels of these variables.

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APPENDIX A

VOLUMETRIC STRAIN-VERSUS-MEAN STRESS DATA FOR AVERY ISLAND CRUSHED SALT DURING QUASI-STATIC LOADING

APPENDIX A

LIST OF FIGURES

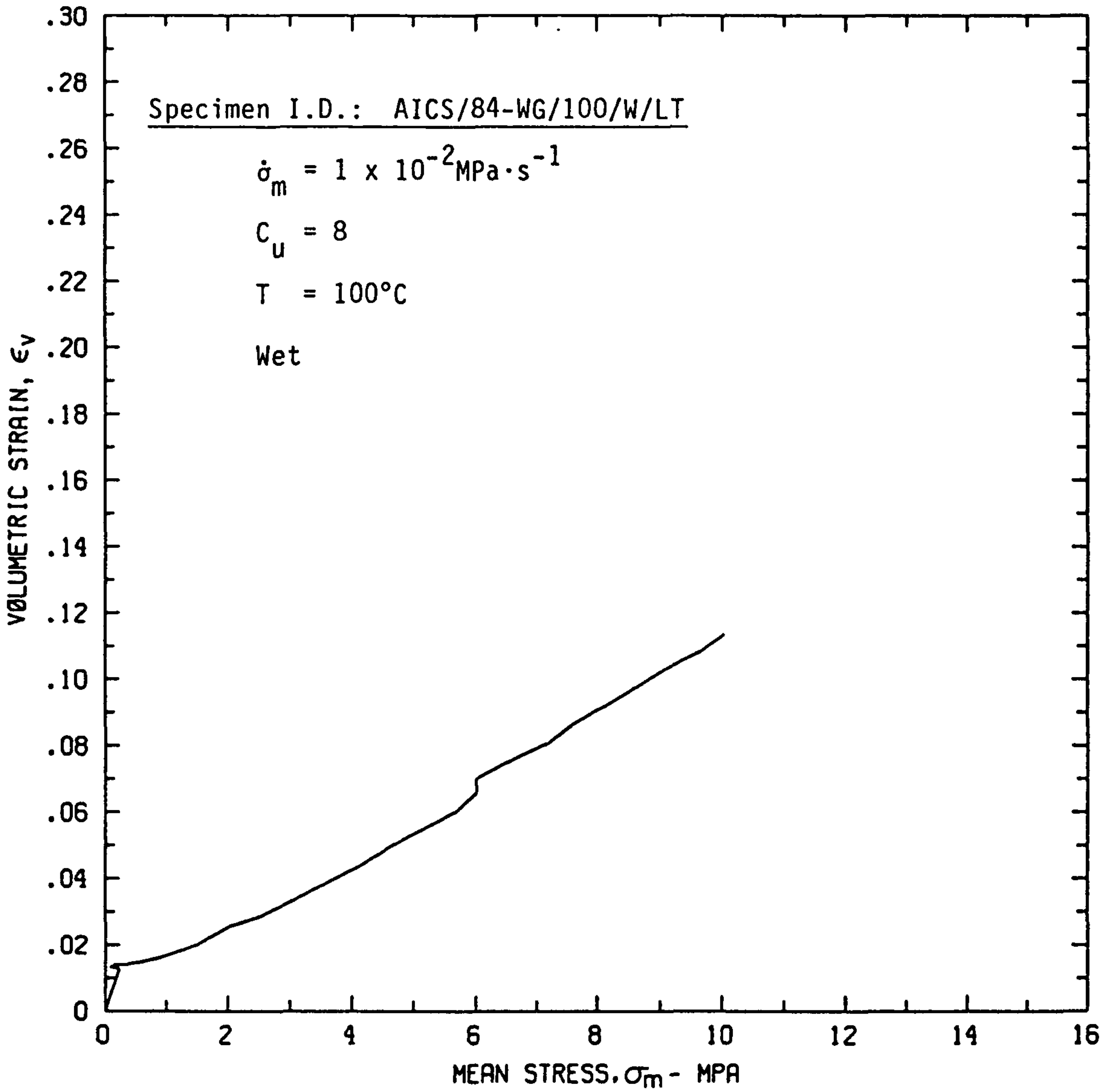

Figure A-1. Measured Volumetric Strain-Versus-Mean Stress for Wet Avery Island Crushed Salt at a Temperature of 100°C and C_u of 8

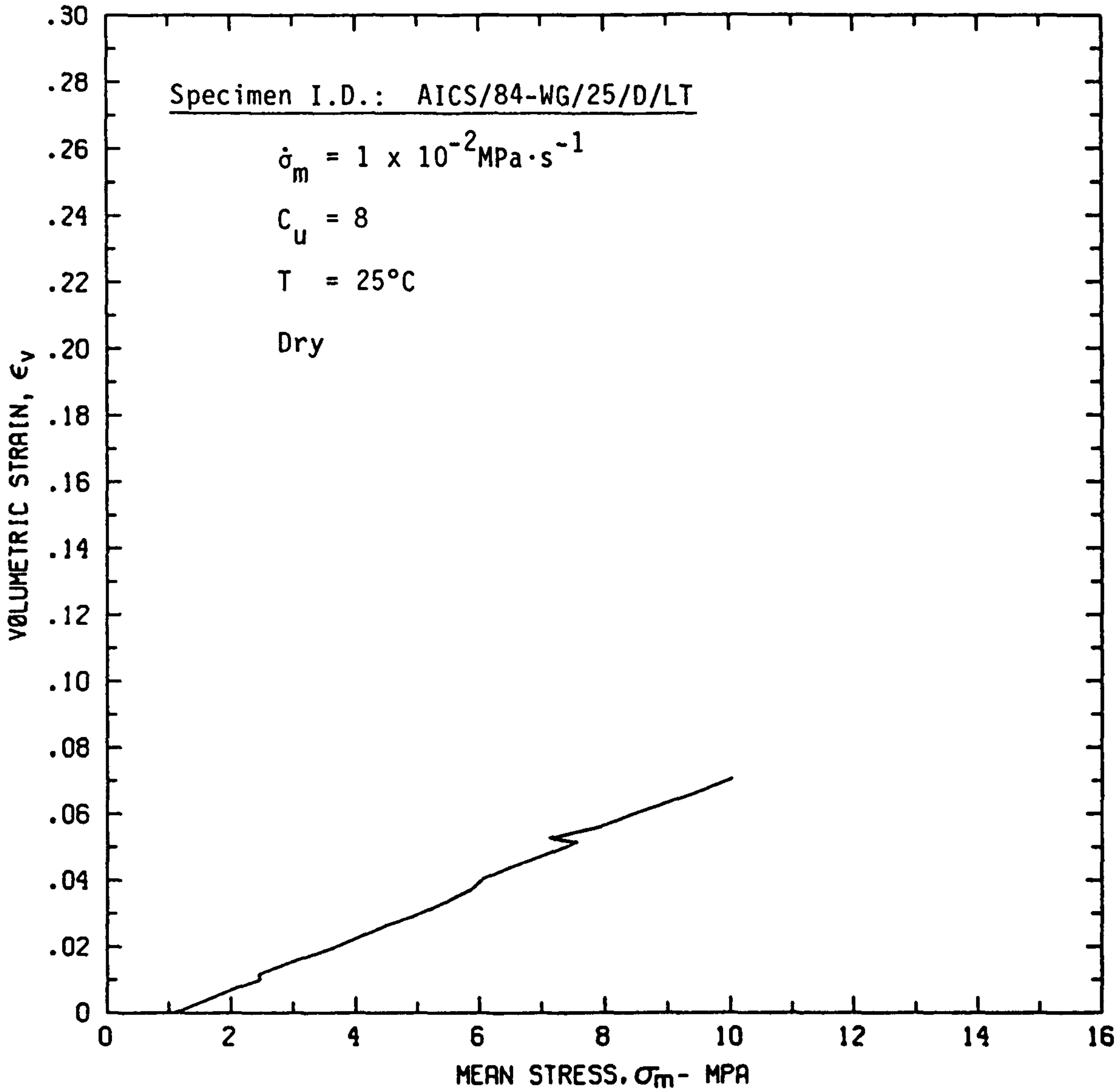

Figure A-2. Measured Volumetric Strain-Versus-Mean Stress for Dry Avery Island Crushed Salt at a Temperature of 25°C and C_u of 8

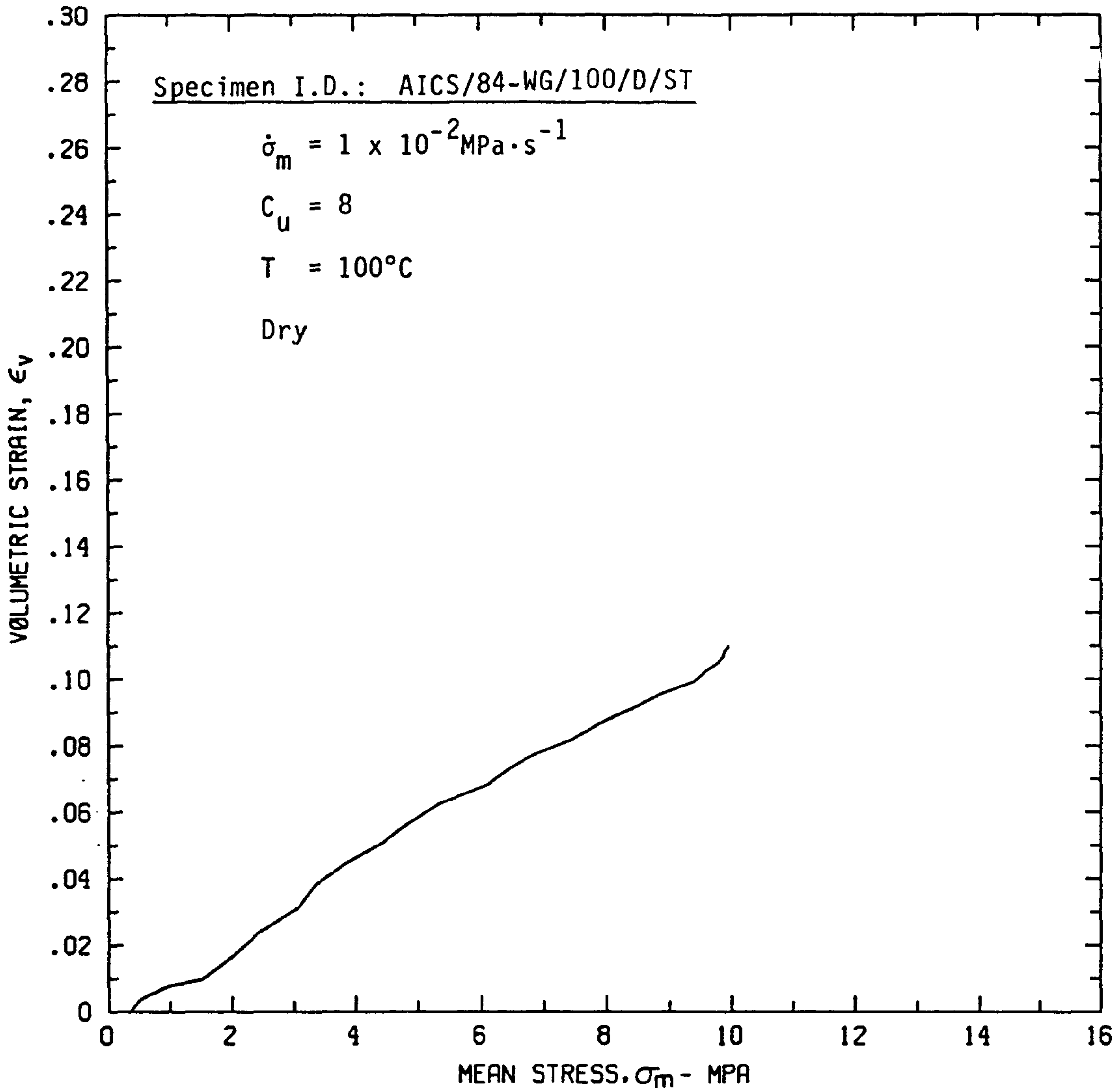

Figure A-3. Measured Volumetric Strain-Versus-Mean Stress for Dry Avery Island Crushed Salt at a Temperature of 100°C and C_u of 8

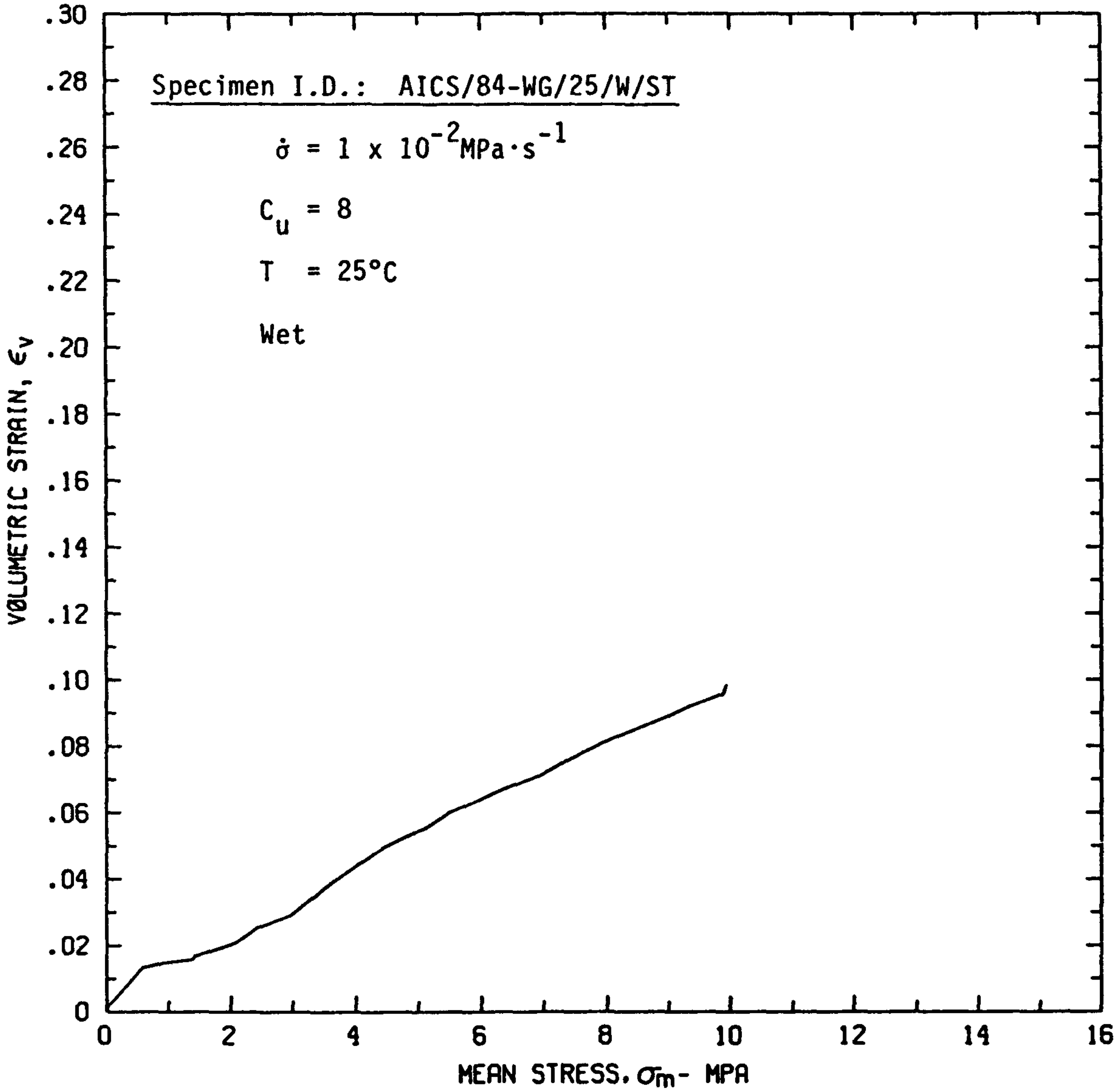

Figure A-4. Measured Volumetric Strain-Versus-Mean Stress for Wet Avery Island Crushed Salt at a Temperature of 25°C and C_u of 8

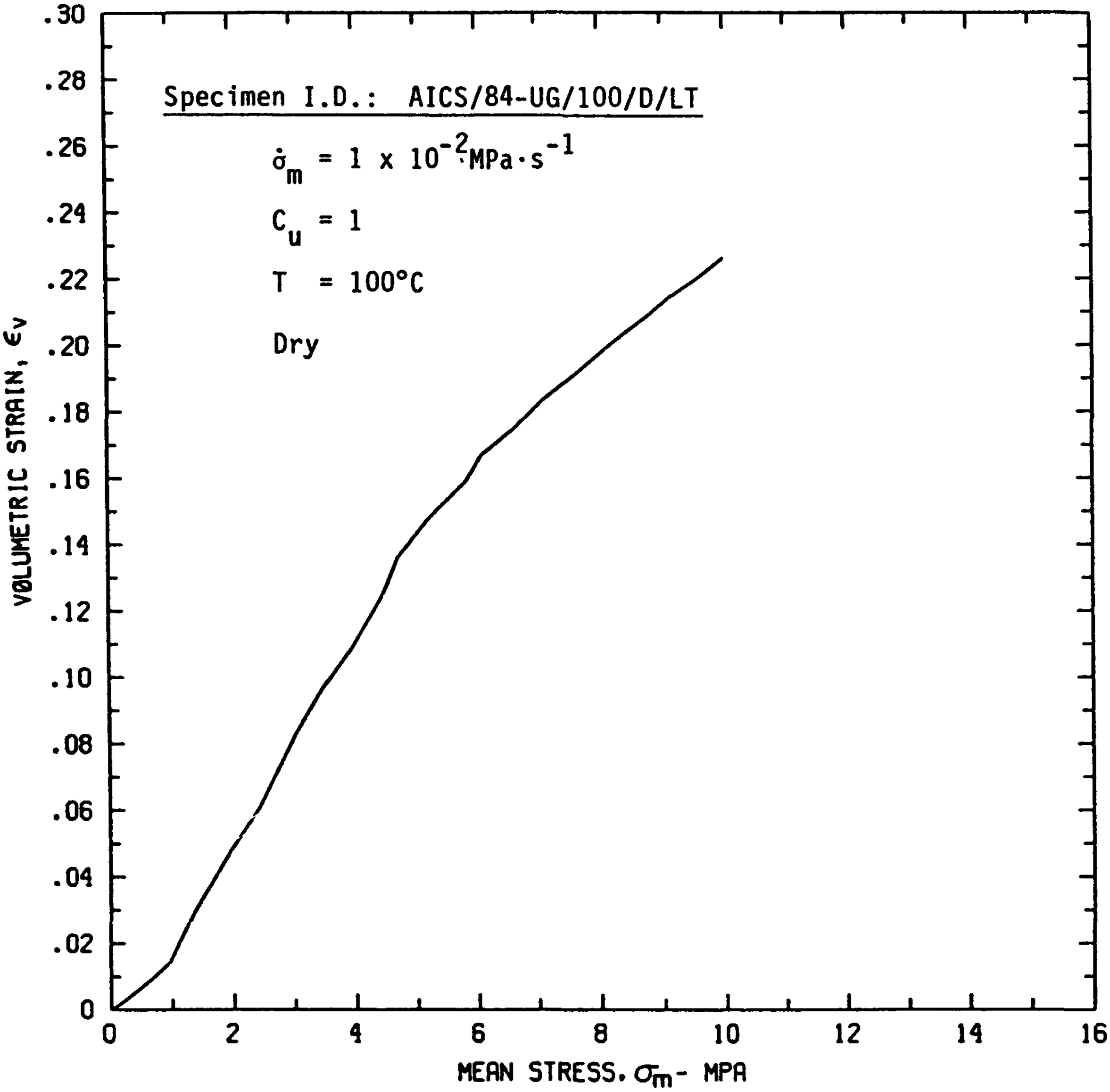

Figure A-5. Measured Volumetric Strain-Versus-Mean Stress for Dry Avery Island Crushed Salt at a Temperature of 100°C and C_u of 1

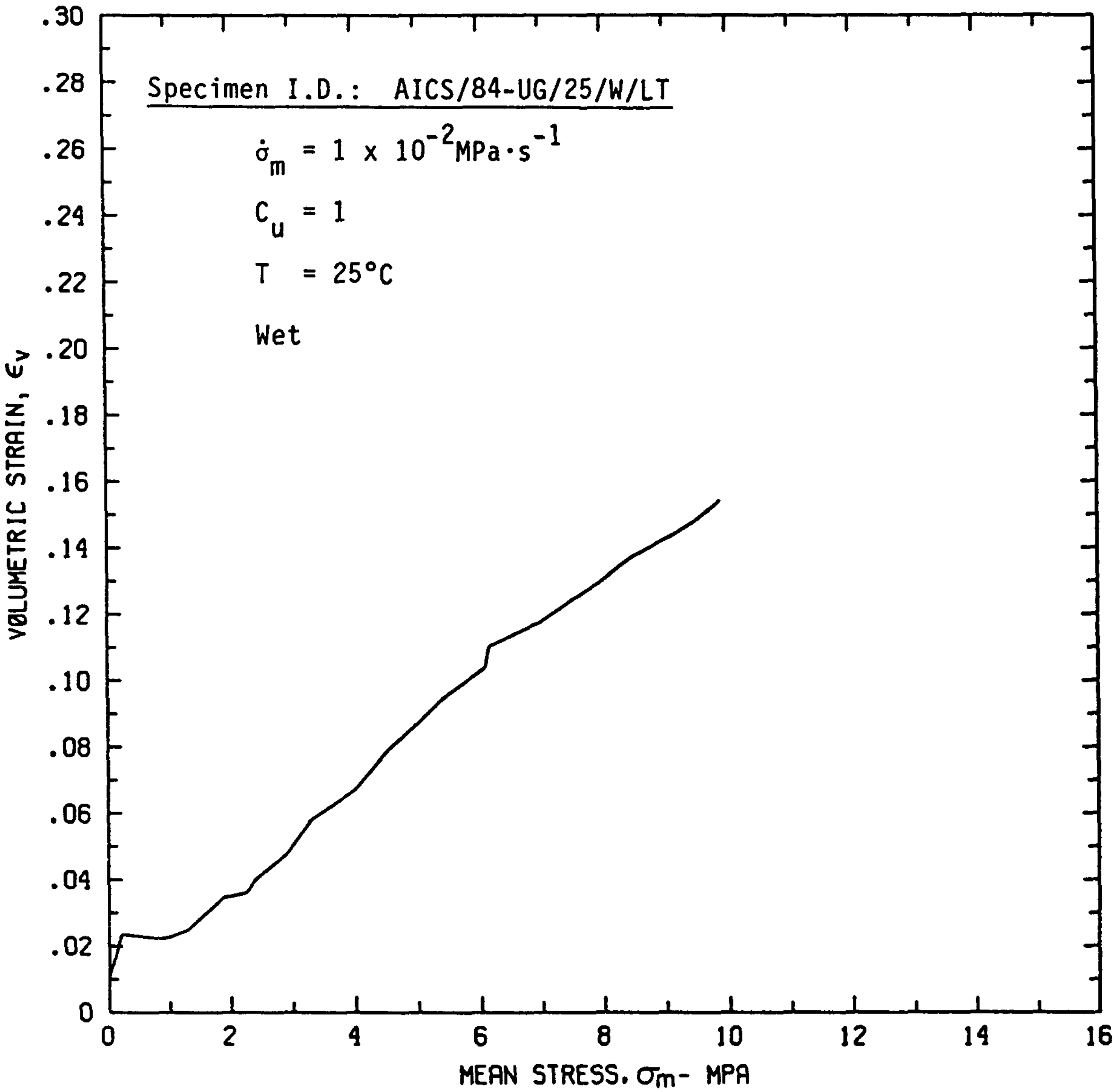

Figure A-6. Measured Volumetric Strain-Versus-Mean Stress for Wet Avery Island Crushed Salt at a Temperature of 25°C and C_u of 1

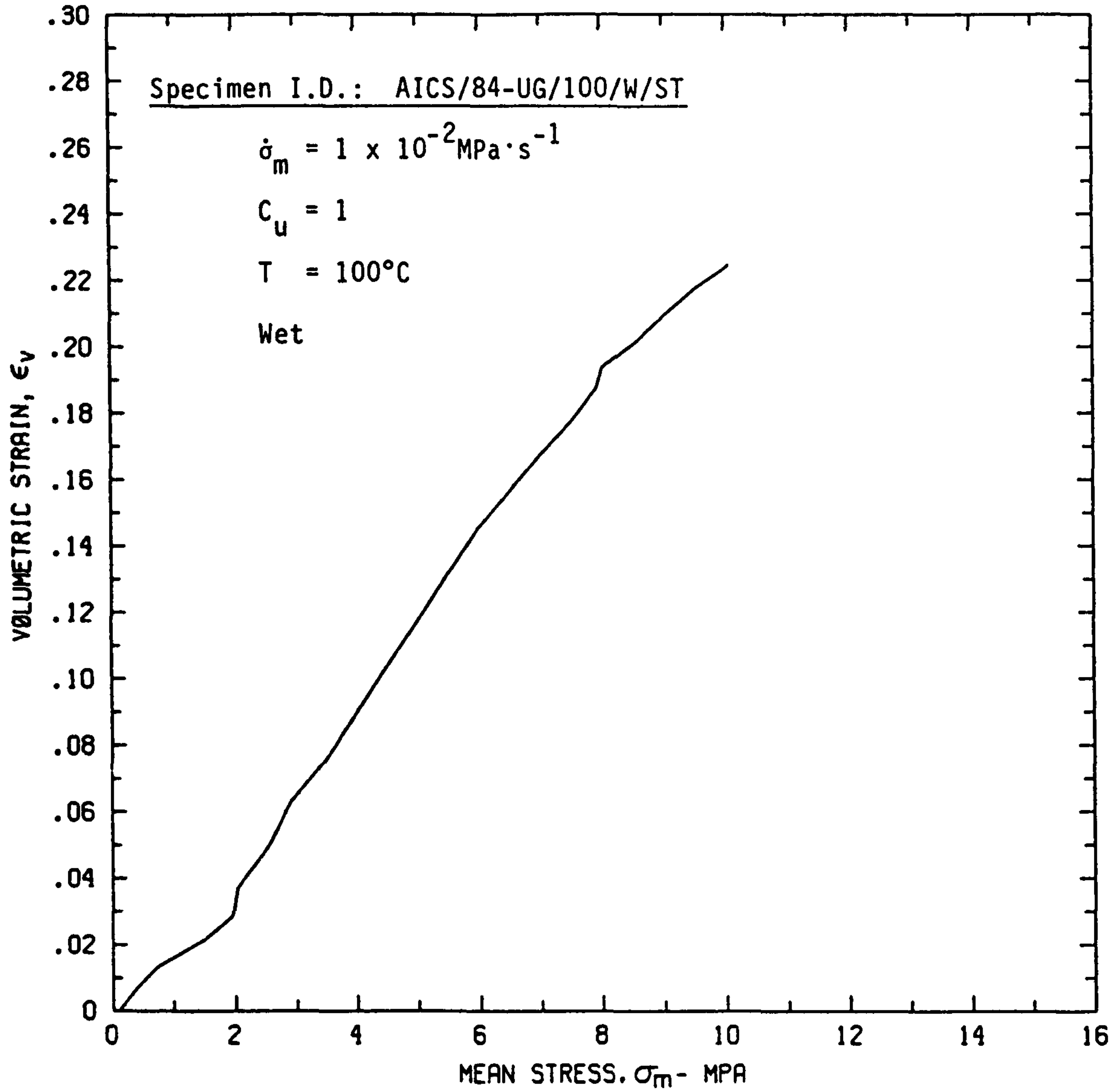

Figure A-7. Measured Volumetric Strain-Versus-Mean Stress for Wet Avery Island Crushed Salt at a Temperature of 100°C and C_u of 1

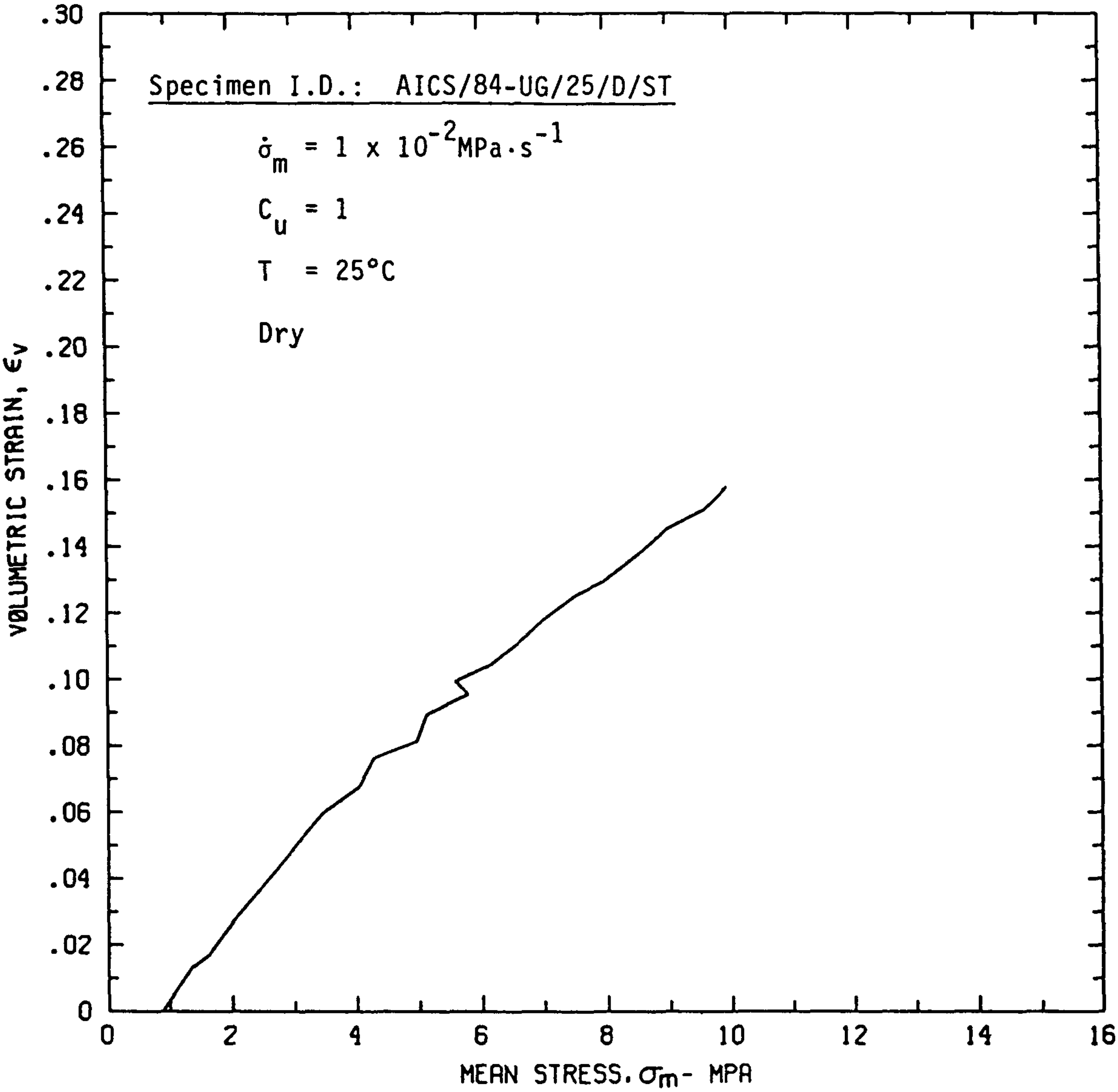

Figure A-8. Measured Volumetric Strain-Versus-Mean Stress for Dry Avery Island Crushed Salt at a Temperature of 25°C and C_u of 1

APPENDIX B

VOLUMETRIC STRAIN-VERSUS-TIME DATA FOR AVERY ISLAND CRUSHED SALT DURING CONSOLIDATION (CREEP)

APPENDIX B

LIST OF FIGURES

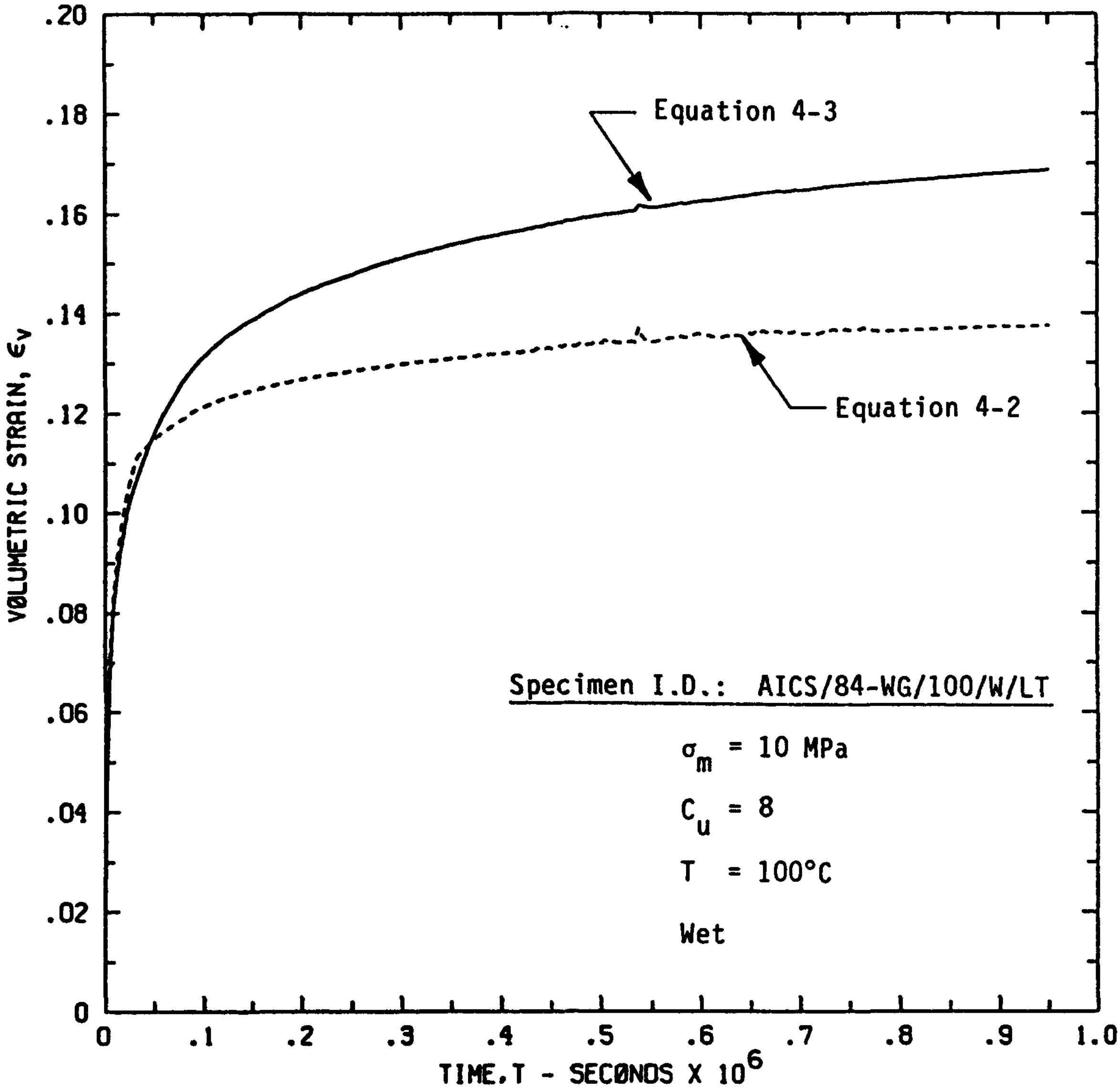

Figure B-1. Measured Volumetric Creep Strain for Wet Avery Island Crushed Salt at a Temperature of 100°C and C_u of 8

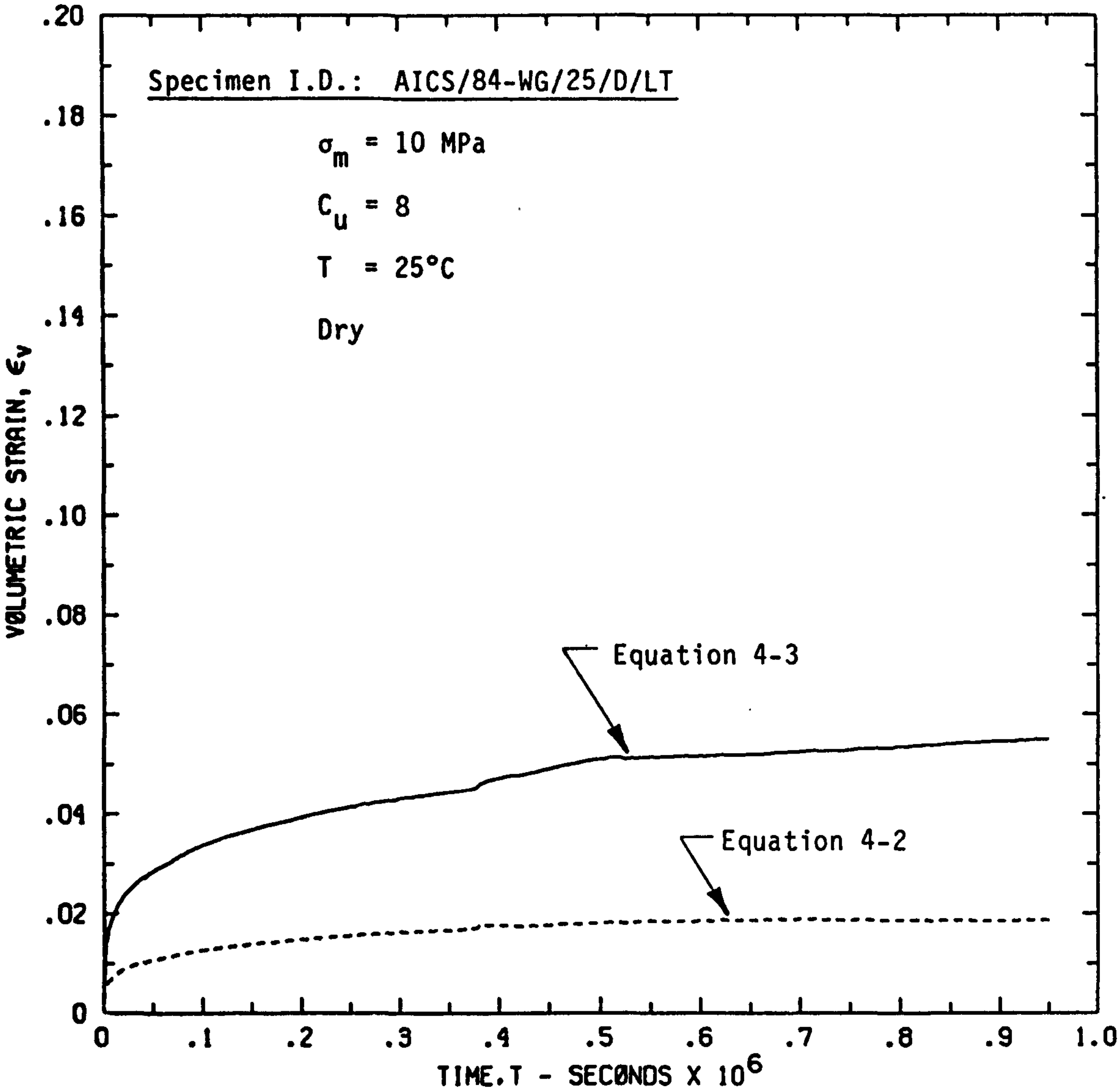

Figure B-2. Measured Volumetric Creep Strain for Dry Avery Island Crushed Salt at a Temperature of 25°C and C_u of 8

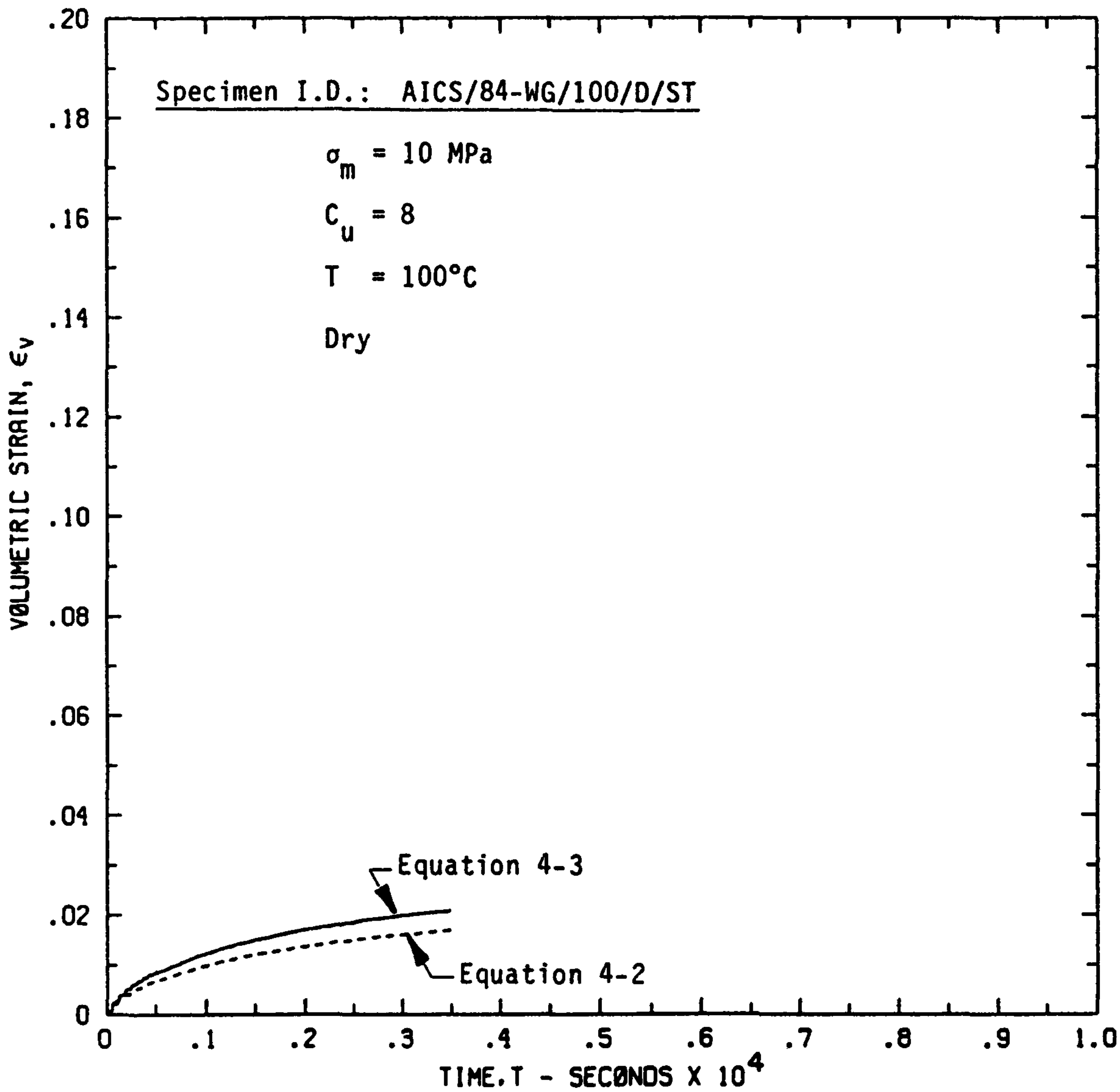

Figure B-3. Measured Volumetric Creep Strain for Dry Avery Island Crushed Salt at a Temperature of 100°C and C_u of 8

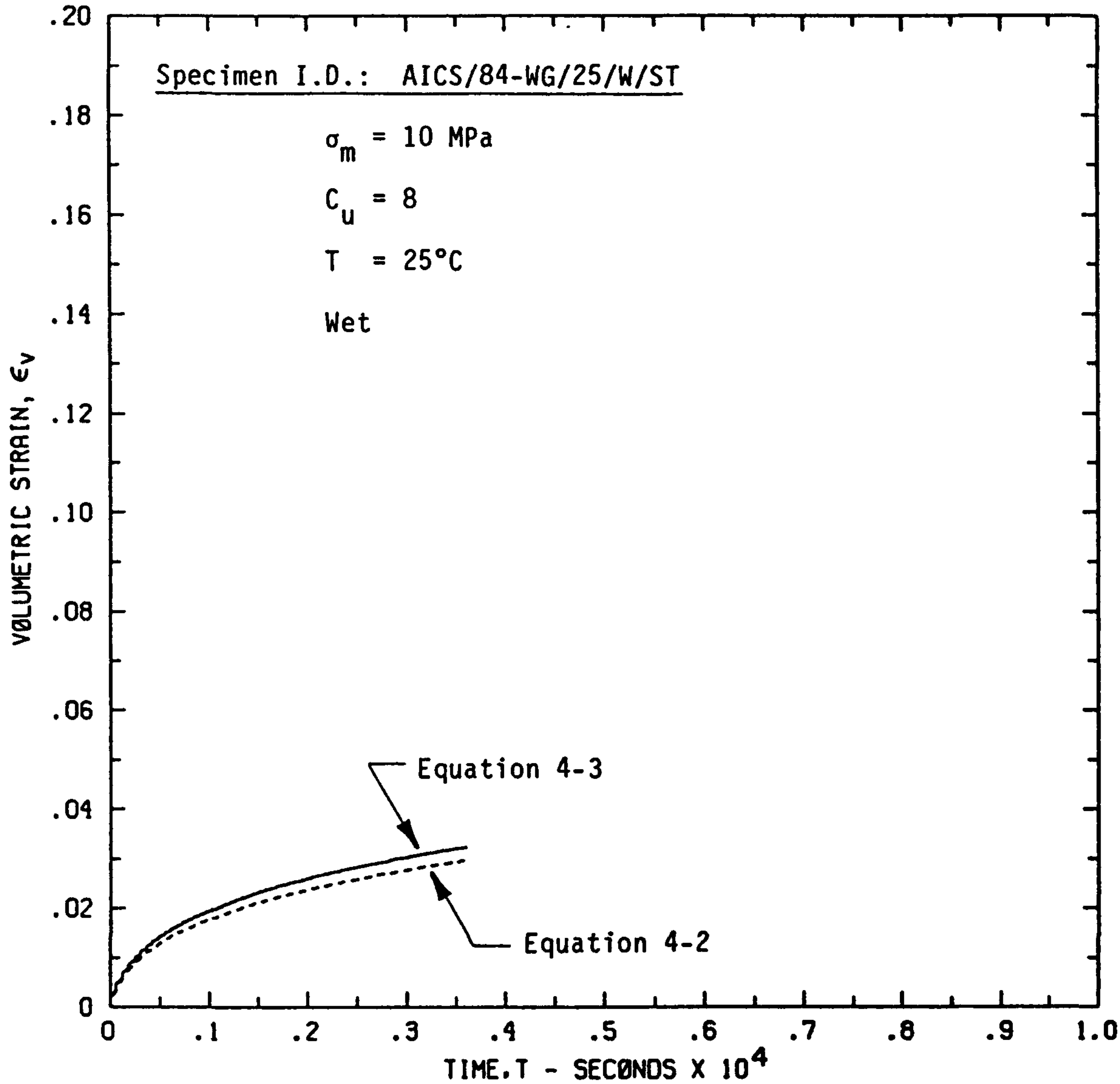

Figure B-4. Measured Volumetric Creep Strain for Wet Avery Island Crushed Salt at a Temperature of 25°C and C_u of 8

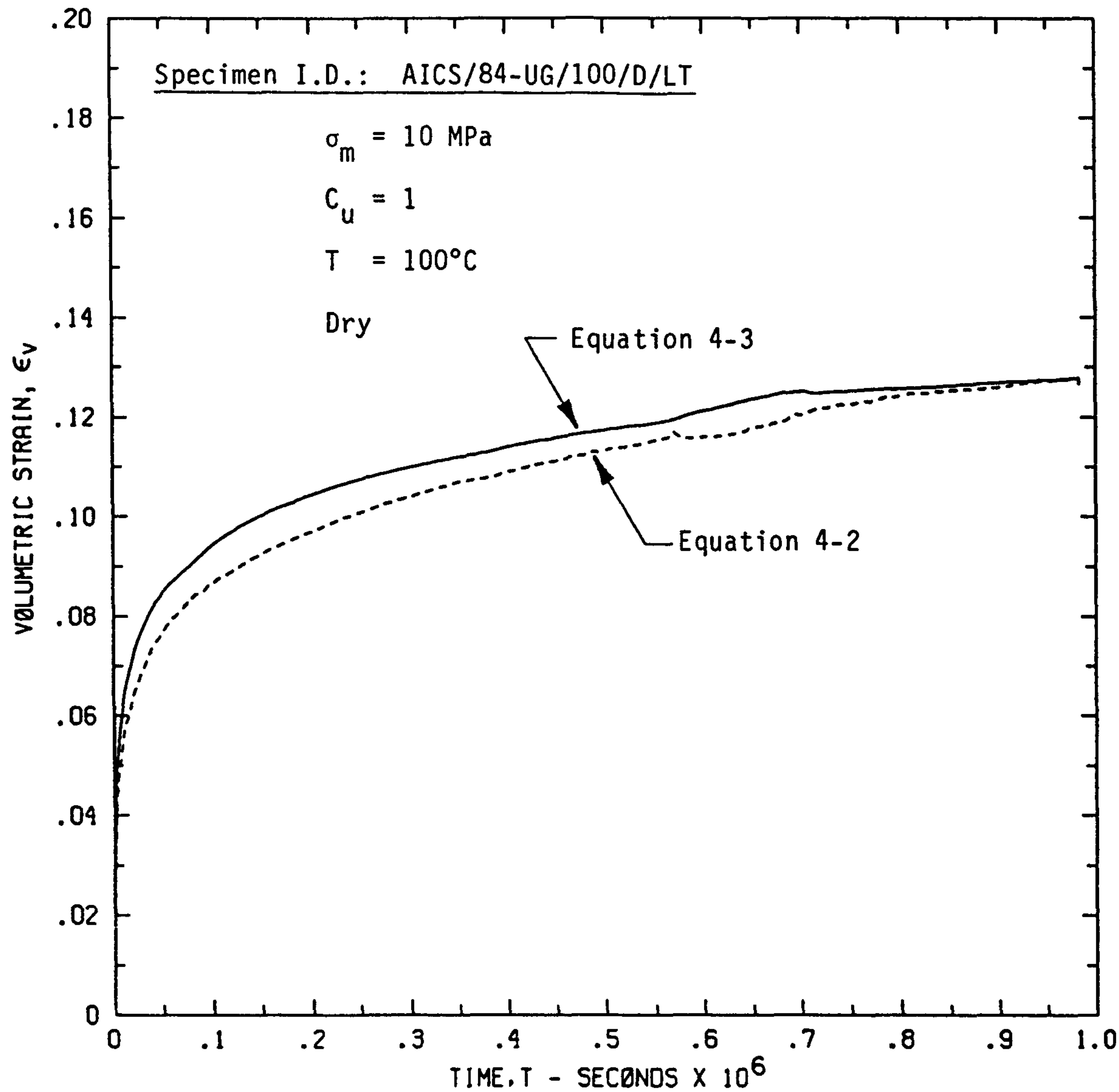

Figure B-5. Measured Volumetric Creep Strain for Dry Avery Island Crushed Salt at a Temperature of 100°C and C_u of 1

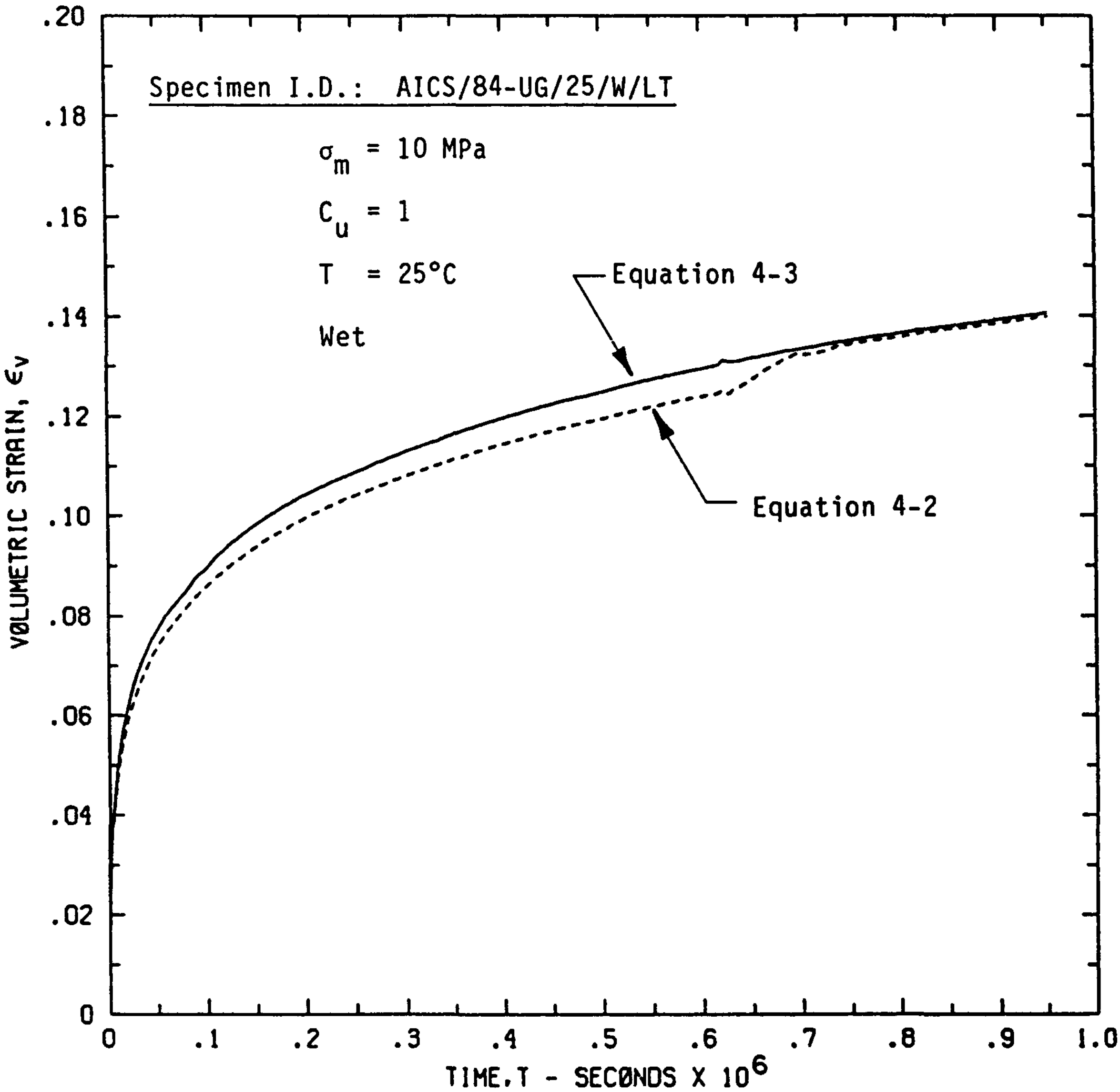

Figure B-6. Measured Volumetric Creep Strain for Wet Avery Island Crushed Salt at a Temperature of 25°C and C_u of 1

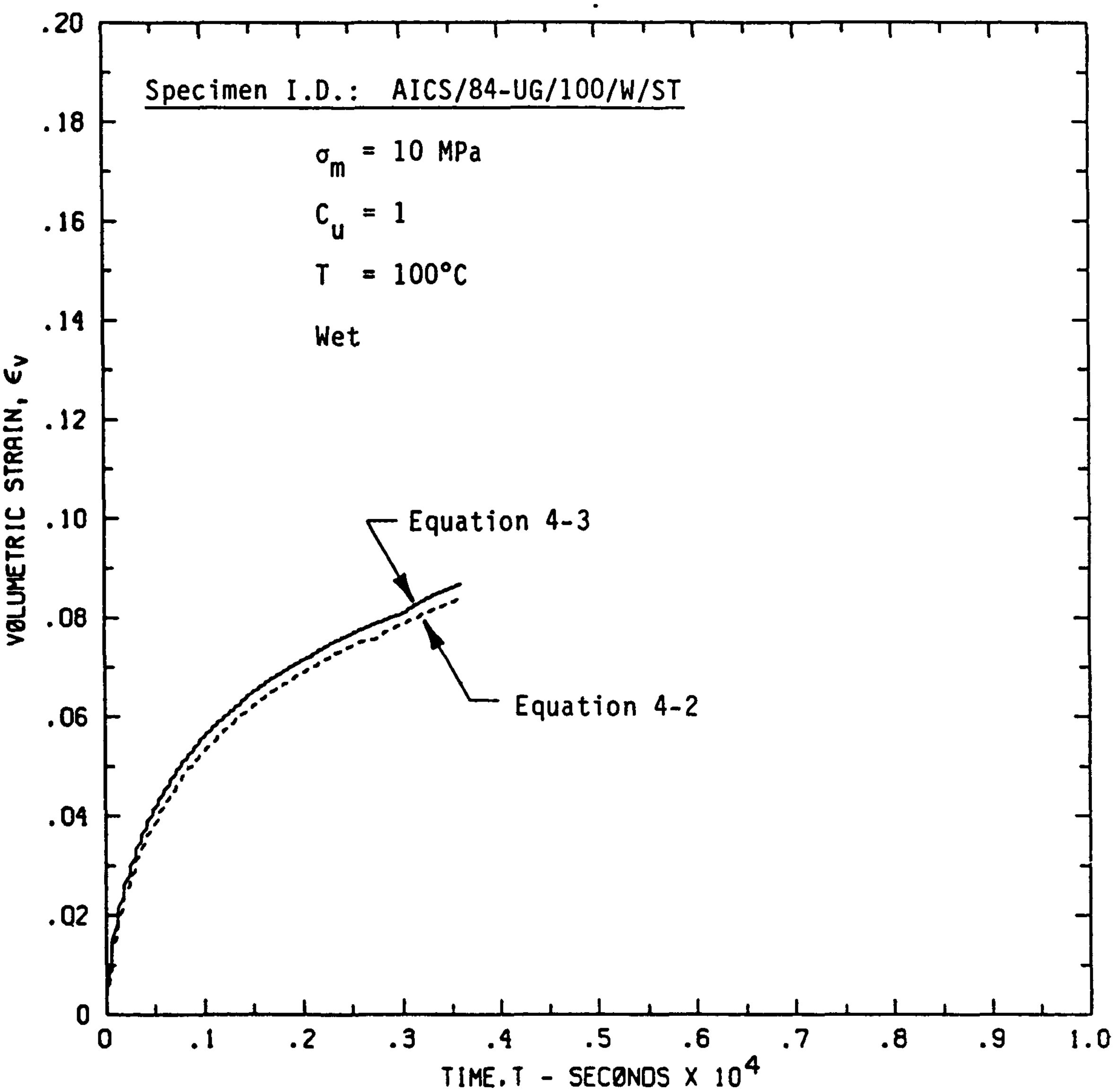

Figure B-7. Measured Volumetric Creep Strain for Wet Avery Island Crushed Salt at a Temperature of 100°C and C_u of 1

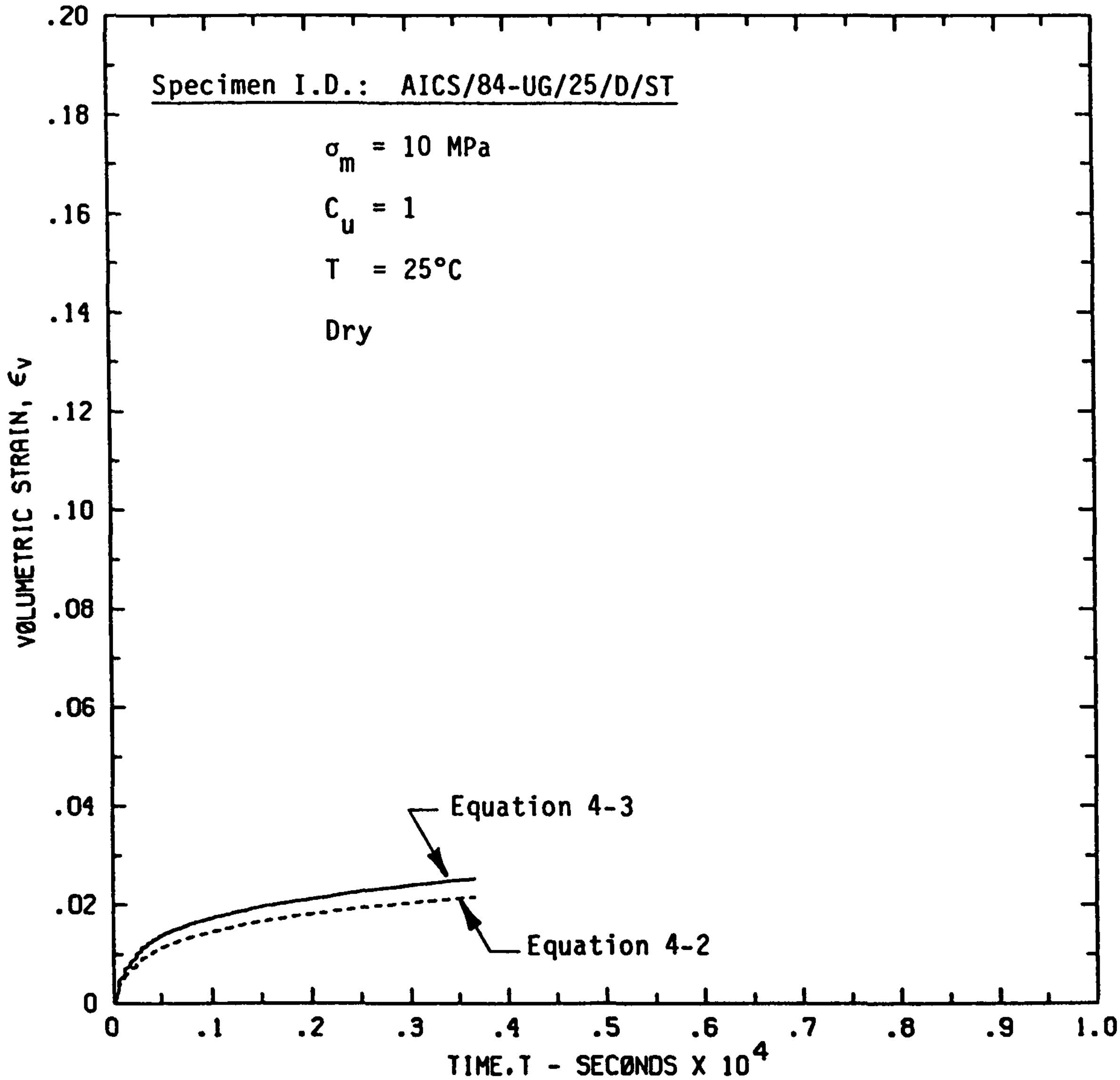

Figure B-8. Measured Volumetric Creep Strain for Dry Avery Island Crushed Salt at a Temperature of 25°C and C_u of 1.

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